NOTES ON PRACTICAL PHYSICS

A. H. FISON

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NOTES ON PRACTICAL PHYSICS

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PREFACE

In the following pages I have attempted to supply a want that I have felt very seriously in my experience of conducting large classes in Practical Physics. The "Notes" are intended to be literally "notes upon" rather than full descriptions of the experiments to which they refer, for I have purposely refrained, at any rate in the majority of cases, from giving a complete description, in the hope that with the "Notes" and the apparatus to which they refer before him, a student of fair ability will be able to use his own intelligence, supplementing the information supplied so as to carry out the experiment satisfactorily. I feel confident that, carried out in some such way as is thus suggested, work in Practical Physics would have a higher educational value than it too frequently has.

No doubt, many, and perhaps the majority of students will require more assistance than is contained in the "Notes," and this will naturally be supplied by the demonstrator, though I believe there to be abundant room for the demonstrator to exercise restraint in the exhibition of his demonstrating powers, and that it is profitable for a student to allow him to wrestle for a time with his difficulties before bringing the armament of superior knowledge to his aid.

As the student is assumed to have the actual apparatus before him while reading the "Notes," diagrams seldom appear necessary, but they have been introduced whenever such a course has seemed advisable.

A rough attempt has been made to indicate by the addition of the letters A, B, and C to the titles of the experiments, their actual values as methods of physical science, other than their use as laboratory exercises. A denotes that the experiment is capable of a very high degree of accuracy, though generally with the aid of more refined apparatus than is assumed to be at the disposal of the student, and that it is practically used in physical research. B denotes that the method, although used practically, does not admit of such great accuracy, and C that the method would not be used in actual practice, and that it is merely suggested as an instructive laboratory exercise.

The Tables of Logarithms and Trigonometrical Ratios are reprinted from Professor J. Perry's *Practical Mathematics*, by permission of the Controller of H.M. Stationery Office.

A. H. F.

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NOTES ON PRACTICAL PHYSICS

CHAPTER I

ADVICE AND SUGGESTIONS

1. (*a*) THE student should remember, in all experimental work, that, unless the closest attention is given throughout to the meaning and significance of the observations he makes, his work is unprofitable, and that he would do better to be otherwise employed.

(*b*) The value of physical observations mainly depends upon the accuracy and refinement with which they are effected, and every experiment described in the following pages is to be conducted with the highest accuracy of which the means admit. In all cases, for instance, in which measurements are made by scales, as in measurements of length by meter scales, measurements of temperatures by thermometers, and measurements of deflections of the magnets of galvanometers by scales of degrees, the quantity measured is to be estimated by eye to a tenth part of the smallest division of the scale. In making these and other measurements a pocket magnifying-glass is of great assistance, and the student should never be without one.

(*c*) It will not generally be necessary for the student to write a full description of the experiment in his note-book, a reference to a work in which the experiment is described, the present one, for instance, being sufficient. *Every quantity* *actually observed must, however, be recorded*, and the manner in which the desired result is deduced from the observations must be made clear. A few illustrations are given at the end of this book (Chapter X.) of the work that should actually appear in the note-book in the case of a few selected experiments.

(*d*) The student must not allow the record of his observations to be disfigured and his work confused by arithmetical calculations. Work of this character may be carried out on scribbling paper. Even with the arithmetic, however, the work should be neatly and horizontally expressed, and not scrawled anyhow all over the page.

(*e*) Let the number of significant figures used in expressing the final result of every physical measurement have some relation to the degree of accuracy that is possible of attainment. If, for instance, the magnitude of a quantity, such as a specific heat, depends upon and is proportional to the reading of an interval of temperature, and if, with the thermometer provided, it is impossible to read the interval with certainty to within 1 part in 100, it is not only useless to express the result by six significant figures, but doing so would be a clear indication that the conditions that limit the accuracy possible of attainment have not been realised. Judgment must be exercised in deciding how many significant figures should be used in every case, but a good general rule is to be content with four and not with fewer, though in many cases the fourth figure will have no physical value.

(*f*) Avoid the reverence with which the greater number of students regard the position of a decimal point as a criterion of accuracy. Remember that that position depends solely upon the unit in terms of which the quantity is expressed. Thus, a length that should happen to be exactly 5207·362 cms., which would be incapable of certain measurement as such by any method known to science, would, with a measuring instrument that should be capable of measuring to an accuracy of 1 part in 5000, be recorded as 52,070 millimeters, if the millimeter were selected as the unit of length, or as 0·05207 kilometers, if the kilometer were selected as the unit. Both results are expressed with equal accuracy, though one is given to five decimal places, while in the other the figure in the units place is replaced by a zero.

(*g*) The result of every experiment should be verified, if time allows, by repetition. It is sometimes advisable to vary the conditions to a greater or less degree in the second trial.

(*h*) Most calculations connected with physical measurements are greatly facilitated by the use of logarithms, and the student who is unacquainted with their use will find that an hour or two devoted to their practice will save many hours of subsequent labour. A slide-rule may frequently be used with advantage, and the common form of 10-inch slide-rule, which will perform the operations of multiplication and division to an accuracy of 1 part in 500, is sufficiently accurate for every experiment described in these "Notes" with the exception of those indicated by the letter A.

2. Errors and Corrections.—In no case is it possible to make any physical measurement with absolute accuracy. An absolutely accurate measurement, if made, would be the result of chance, and no means would exist by which its accuracy could be established. In many cases, however, when the cause of error is recognised, it may be approximately allowed for by the application of a *correction*, and instances of this will appear in the sequel. Technically, the error of an observation is the amount by which the observed exceeds the true value, the error being regarded as negative when the observed quantity is less than the true value, while a *correction* is a quantity to be added to the observed quantity to give the actual value. It follows that errors and corrections are equal but of opposite signs.

Graphs.—Many physical laws express the manner in which one quantity, the *dependent variable*, depends upon another, the *independent variable.* Thus, in the statement that the volume of mercury *depends* upon its temperature, temperature is the *independent* and volume the *dependent* variable. In the statement that the light emitted by an electric lamp *depends* upon the current traversing the filament, the current is the *independent* and the light the *dependent* variable. In such cases, the significance of the law is often most clearly realised by the construction of a graph. When this method is adopted, an accepted convention is to plot the independent variable horizontally from left to right and the dependent variable vertically upwards. Neglect of this simple rule in the construction of graphs frequently gives great trouble in their interpretation.

CHAPTER II

LENGTH, MASS, AND TIME

3. Every physical measurement is essentially a comparison between the quantity measured and another quantity of the same kind that has been arbitrarily selected as a standard or *unit*. Thus the statement that the height of a man is 6 feet is a comparison between the length of the man and another length, a foot, which in this case has been selected as the unit of length, and the statement that the strength of an electric current is 20 amperes is a comparison between the strength of a given current and another current—the ampere—which has been selected as the unit electric current.

There must consequently be a unit of every kind of quantity that is capable of measurement. In some cases, however, units of one kind are obviously derived from those of another. Thus, the cubic foot, as the unit of volume, is clearly derived from the linear foot, the unit of length, and a velocity of a mile per hour, a unity of velocity, is derived from two other units, the mile and the hour, which are units of length and time respectively. The practice of deriving the more complex units from simpler ones has been carried so far that it has been found possible to derive the units of all quantities with the measurement of which science is concerned from three simple or *fundamental* units, viz. those of length, mass, and time. The particular units of length, mass, and time that have been selected as forming the foundation of all other units are the centimeter, the gramme, and the second respectively. The system of measurement founded on these is consequently known as the centimeter-gramme-second, or the C.G.S. system of units.

THE MEASUREMENT OF LENGTH

4. Lengths are commonly measured in the laboratory by the aid of wooden scales a meter long, which are divided into centimeters and millimeters. When great accuracy, however, is required, a metal scale is essential. The accuracy of all scales depends upon their ultimate reference to a standard rod, a meter in length, preserved in Paris.

5. When measuring a length by a meter scale, the graduated edge of the scale must, if possible, be brought *into actual contact with* the line to be measured. In the measurement of straight lines ruled on paper, for instance, this is generally possible. Often, however, it is not possible, and in every such case the student should consider the best means to avoid possible error. Several causes of error may arise, the most common being due to "parallax." If, for instance, the scale of a thermometer is etched on the front of the tube, the true reading of the thermometer will only be given if the line from the eye to the thermometer is at right angles to the tube. When the eye is displaced either way in the direction of the length of the tube, the reading alters, the cause of the alteration being obvious. The alteration is known as *parallax*. A good way of avoiding parallax error in this case and in many others is to hold a plane mirror behind the tube and in contact with it. When the position of the eye is so adjusted that it sees its own reflected image directly behind the top of the column of mercury, the line of vision is necessarily at right angles to the mirror and tube, and parallax error is avoided.

6. A common, though inexcusable, fault of construction in many scientific instruments consists in fixing the scale parallel to, but at a considerable distance from, the quantity the length of which is to be measured. In such a case, it is impossible to feel confident that serious error has not been introduced if the eye only is relied upon, but the error may sometimes be reduced by holding an edge of a visiting card along the graduated edge of the scale, adjusting it at the same time so that the adjacent edge passes through the point the position of which is required.

7. When using a meter scale, lengths must be estimated by eye to a tenth part of a millimeter, the smallest scale division. With a very little practice an error of two-tenths of a millimeter should be impossible.

8. When it is desired to measure lengths with the highest possible degree of accuracy, the cathetometer or the travelling microscope must be used. The examination of these instruments will suggest the principles involved in their action.

The Vernier

9. The vernier is a simple contrivance for measuring a fractional part of the smallest division of a scale with an accuracy that is far higher than is possible by simple eye estimation. It consists of a short *vernier* scale that slides beside a main scale. The vernier scale is either fixed to the body to be measured or some method is provided by which it can be accurately adjusted to some point on it. It will be sufficient to describe the method of reading the vernier, and the student should follow this with a vernier before him. He should not, however, remain content without mastering the principle involved, which after using the instrument should be obvious with a little thought.

Set the zero, or index mark, of the vernier scale against any division of the main scale. It will be noticed that other marks of the vernier do not coincide with marks of the main scale, showing the lengths of the divisions of the two scales to be different. The lengths of the vernier divisions are generally, though not always, the shorter. With the index of the vernier accurately adjusted to any division of the main scale, follow the vernier scale, and count the number of vernier divisions from the index mark to the point at which a vernier division again comes into coincidence with a division of the main scale. This will generally be the last division on the vernier. Calling it the nth, the vernier is constructed to read to $1/n$th of a division of the main scale. Now, to read the position of the index mark of the vernier when it is in any position, observe how many divisions of the vernier are counted from the index mark before a coincidence between a vernier division and a main scale division occurs. Do not pay any attention to the particular division on the main scale. This number of vernier divisions is the number of $n$ths of a main scale division that the index mark is removed from the scale division next below it. The description involves many words, but the practice of reading a vernier becomes quite simple with a little practice.

Micrometer Screw Gauge and Vernier Callipers

10. The student should retire with the instruments to a quiet corner of the laboratory and worry out the principles of their action for himself.

Mass and its Measurement—The Balance

11. The mass of a body is generally defined as the amount of matter it contains. The definition is open to serious and indeed fatal criticism, but it must suffice for the purpose of this work.

The unit of mass in the C.G.S. system is the gramme, which is the one-thousandth part of a standard mass of 1000 grammes preserved in Paris. The gramme was originally intended to be as nearly as possible the mass of a cubic centimeter of water at 4° C., the temperature of its maximum density. According to the most recent determinations, the mass of a cubic centimeter of water at this temperature is actually 1·000013 grammes. For all ordinary purposes, however, a gramme may be regarded as the mass of a cubic centimeter of water at 4° C.

12. Every body is attracted towards the earth by a force known as its *weight*. It is of the utmost importance that the student should master the distinction between *mass* and *weight*. The weight of a body varies quite appreciably as it is carried to different parts of the earth, but its mass necessarily remains the same. It so happens from the law of gravitation that the weights of different bodies in the same locality are proportional to their masses, so that, under these conditions, equal masses have equal weights. It is thus possible to determine the equality of masses from the equality of their weights. This is effected in the use of the balance, which actually tests equality of weights, though its ultimate purpose is to test equality of masses.

The Operation of Weighing (A)

13. In the following description, the student is assumed to have a sensitive balance before him.

When swinging freely the beam rests by an agate knife edge rigidly attached to it upon an agate plane that is carried on the central pillar, and the pans are hung from agate planes that rest on knife edges attached to the beam. When not in use, however, a framework is brought into position by turning a handle in front of the balance case so that all moving parts are supported independently with the knife edges and planes separated. The releasing and supporting of the beam must always be effected gently, and nothing must be added to either pan while the beam is free.

Before weighing, test the accuracy of the zero by gently releasing the beam with nothing in either pan. The act of release will generally leave the balance in a condition of slight oscillation, and the long pointer attached to the beam will move slowly from side to side in front of the scale at the foot of the pillar. It will not generally oscillate to equal distances on either side of the zero, nor is it necessary that it should do so. The point of the scale on either side of which the oscillations are equal should be observed and entered in the note-book as the "corrected zero." If the corrected zero is off the scale, correct it by adjusting one of the small screws at the end of the beam, clamping the beam, of course, before doing so.

Now, having clamped the beam, place the object to be weighed in the left-hand pan, and add masses, the so-called "weights," on the right, always transferring a weight by the forceps without touching it by the hand. Release the beam and decide from the movement of the pointer which side is the heavier. Clamp the beam, add different "weights," and continue until a balance is obtained. The smallest weight used is 0·01 gramme, the final balance being obtained from the use of a "rider" weighing 0·01 gramme, which rides on the beam, which is for this purpose graduated in tenths. Thus when the rider is at one-tenth the length of the beam from the centre, its effective weight is 0·001 gramme, and so on. When a balance is obtained, record the total weight on the right, including the effective weight of the rider. This gives the so-called weight, truly the mass, of the body.

The student must clearly realise that the so-called weights of a balance are actually masses, their weights being the forces with which the earth attracts them. The term *weights*, as applied to pieces of metal, is, however, of such extended use that it is not advisable to attempt to avoid it, and consequently it will wilfully be so used in this work. With a little experience, however, this will involve no confusion.

14. *Correction for the Buoyancy of Air on the Balanced Masses.* —When weighing bodies of low specific gravity, and when the highest accuracy is required, it is necessary to introduce a correction for the fact that both the body weighed and the weights themselves are buoyed up to some extent by the air. An equation giving the correction is readily deduced from the Principle of Archimedes (Art. 21), and is given together with values of the corrections calculated from it in Table II., p. 135. When the mean specific gravity of the weighed body is greater than that of water, the correction is always less than 1 part in 1000, and may often be ignored.

A good balance, when used with all possible precautions, is capable of weighing a mass of 100 grammes to an accuracy of 1 part in 1,000,000. No other physical measurement is capable of such accuracy.

15. To allow for the fact that the arms of the balance are not probably of precisely equal length, it is necessary, when great accuracy is required, to weigh the body first in one pan and then in the other. Any difference is due to inequality in the arms, and the actual weight is the square root of the product of the two weighings. The mechanical principle involved is very simple.

The Measurement of Time

16. The unit of time selected in the C.G.S. system is the second, which is defined as the 86,400 part of the mean solar day. Time is measured in the laboratory either by clocks or watches, and of recent years stop-watches have become common. The writer must confess that he regards these with very little affection. For the measurement of short periods a loud-beating clock or even a metronome is far superior, while for long periods a watch provided with a seconds hand gives results of higher accuracy than the stop-watches that seem to be regarded as good enough for the laboratory.

CHAPTER III

SPECIFIC GRAVITY—THE PRESSURE OF GASES

17. The *specific gravity* of a substance is defined as the ratio of its mass to the mass of an equal volume of water at 4° C. The qualification "at 4° C." is often omitted, but when the temperature at which many of the following experiments are carried out is more than a few degrees removed from 4° C., appreciable error would result from the omission.

Determination of the Specific Gravity of a Liquid by the Specific Gravity Bottle (A)

18. In its ordinary form the bottle is provided with a perforated stopper. When it is to be filled, the stopper is withdrawn, liquid introduced to fill the bottle, and the stopper reinserted, the surplus liquid escaping through the perforation. No more force should be employed than is just sufficient to cause the stopper to grip. The liquids used should be rather warmer than the air, to avoid possible trouble due to their expansion and consequent escape through the perforated stopper during the process of weighing.

Clean the bottle by rinsing with water. Rinse out with spirit to facilitate drying, and after allowing the spirit to drain, dry by holding the bottle well above the flame of a Bunsen burner, at the same time drawing air through it by suction through a glass tube. When cool, weigh (Art. 13). Fill with water, take the temperature of the water by a thermometer with its bulb inside the bottle, insert the stopper, wipe carefully with a dry cloth, and weigh again. Empty the bottle and fill with the given liquid, previously rinsing out with a small quantity. Take the temperature, dry, and weigh again. The temperature of the liquid should be as nearly as possible that of the water used previously, or a correction will be necessary for the variation in volume of the bottle with temperature. The sp. gr. of the liquid referred to the water used is at once deduced from the results, and the sp. gr. of the liquid at its actual temperature referred to water at 4° C. may be obtained from Table I., p. 135. Observe the effect of introducing this correction.

The further corrections referred to in Arts. 14 and 15 may also be introduced.

An example of the work that should appear in the notebook in carrying out this experiment is given on p. 129.

Determination of the Specific Gravity of a Solid that is given in Small Fragments (A)

19. Lead shot or pins are convenient for this experiment. If the solid is insoluble in water, weigh a watch-glass, first empty, and then with fragments of the solid upon it. The greatest accuracy will be obtained if these are nearly sufficient to fill the bottle. Deduce the mass of the solid. Weigh together a specific gravity bottle full of water, which should be very accurately at the temperature of the air, noting the temperature, and the solid with the watch-glass. There is no necessity to weigh the empty bottle. Introduce the solid into the bottle, temporarily removed, of course, from the scale-pan, reject the water that overflows, and weigh again after replacing the watch-glass on the scale-pan. The difference between the last two weighings gives the mass of displaced water. Thence find the sp. gr., applying the temperature correction referred to in Art. 18.

20. If the solid is soluble in water, use instead of water a liquid in which it is insoluble, and proceeding as before, find the sp. gr. of the solid referred to the liquid. Then find the sp. gr. of the liquid by the methods of Art. 18, and deduce that of the solid. (Crystals of sulphate of copper and spirit may be used as an exercise.)

Verification of the Principle of Archimedes (C)

21. *The Principle.*—A body entirely immersed in any fluid at rest experiences, by reason of the pressure of the fluid upon it, an upward thrust which is equal to the weight of the fluid it displaces.

Verification.—Select a short glass rod that is just capable of introduction into a specific gravity bottle, and draw out one end of the rod into a hook. Suspend it by a very fine wire from the hook above the pan of a sensitive balance, and weigh it first in air, and then with the rod just immersed below the surface of any liquid contained in a beaker. A possible source of error in this weighing is due to surface tension between the wire and the surface of the liquid, but this, being proportional to the circumference of the wire, may be made very small by selecting a very fine suspending wire. The difference between the two weighings gives the upthrust due to the pressure of the liquid. Next, find the weight of liquid that the rod displaces (Art. 19). This should be equal to the upthrust as determined in the first part of the experiment. Express the result neatly, showing to what degree of accuracy the principle is confirmed.

Determination of the Specific Gravity of a Solid by the Principle of Archimedes (A)

(i.) *For a Solid that is insoluble in and sinks in Water*

22. Weigh the solid, first in air and then in water as described in Art. 21, being careful to remove any bubbles by a small brush. Take the temperature of the water. The difference gives the mass of displaced water, and the sp. gr. of the solid referred to the water actually used at once follows. Referring to Table I., p. 135, find the sp. gr. of the solid at the temperature at which it was weighed in water referred to water at 4° C.

As an exercise, determine the sp. gr. of a metal at 15° C. and again at 25° C.

(ii.) *For a Solid that is insoluble in but floats in Water*

23. Weigh the solid in air. Attach a piece of lead to a fine wire and weigh it in water. Fasten the solid to the lead by a long end of the wire that has been left in attaching the lead, and weigh the solid and the lead together in water. Deduce from the three weighings the upthrust on the solid, and thence its sp. gr., correcting for temperature as before.

(iii.) *For a Solid that dissolves in Water*

24. Select a liquid in which the solid does not dissolve, and, proceeding either as in (i.) or (ii.) as the circumstances demand, find the sp. gr. of the solid referred to the liquid. Then, find the sp. gr. of the liquid (Art. 18), and deduce the sp. gr. of the solid referred to water at 4° C.

Determination of the Specific Gravity of a Liquid by the Principle of Archimedes (A)

25. Select a solid that does not dissolve either in water or the given liquid. The lower the sp. gr. of the solid, provided that it sinks in both liquids, the more accurate the result will be. A glass bulb loaded with shot is very convenient. Weigh the solid successively in air, in water, and in the given liquid, and deduce the sp. gr. of the liquid from the results. Correct for temperature.

Determination of the Mass of a Cubic Centimeter of Water (A)

26. Measure the linear dimensions of some solid of regular geometrical form, using vernier callipers (Arts. 9, 10). Deduce the volume. Weigh the solid, first in air and then in water. Find the mass of displaced water from the Principle of Archimedes, and thence the mass of a cubic centimeter at the temperature of the weighing in water. Deduce the mass of a cubic centimeter of water at 4° C. (Table I., p. 135). Compare with Art. 11.

The gramme was originally determined by such an experiment as this.

27. *Density.*—The density of a substance is defined as the mass of a unit volume of it. In the C.G.S. system, therefore, the density of water is practically 1 (but see Art. 11), and, to the same order of accuracy, sp. grs. are represented by the same numbers as densities. In the British system of units the density of water is 62·3, since a cubic foot of water contains 62·3 lbs.

Determination of the Sectional Area of a Wire (B)

28. *First Method*—the most accurate—*employing the Principle of Archimedes.*—Extend the wire between two clamps, using just sufficient force to straighten it. Make two fine file marks, rather less than a meter apart, upon it, and measure the distance between the marks by a meter scale. Cut the wire at the marks, coil the measured length and weigh it, first in air and then in water. The result gives the mass, and, by Art. 26, the volume of the displaced water, which is, of course, the volume of the wire. Deduce the sectional area from the fact that volume = sectional area × length. Since the method does not supply any test of the uniformity of the sectional area, the result may be regarded as the *mean* sectional area of the wire.

29. *Second Method—by the Micrometer Screw Gauge.*—Turn the screw of the gauge so as to bring the jaws into contact with a slight grip that will be subsequently recognised, and read for any error in the position of the zero. Measure the diameter of the wire at a distance of about 5 cms. from one end, taking the mean of the measurements of two diameters at right angles to one another. Repeat at intervals of 10 cms. throughout the length of the wire, and determine the mean diameter from the complete series of measurements. The square of this multiplied by $\frac{\pi}{4}$ gives very approximately the mean sectional area unless this varies very considerably. Consider why it does not give the true mean area, and think how this might be determined from the observations.

Determination of the Sectional Area of the Bore of a Capillary Tube (B)

30. Attach a short length of india-rubber tube carrying a pinchcock to the given tube. Open the pinchcock, and apply suction to the india-rubber tube so as to draw a thread of mercury about 20 cms. long into the glass tube. Then close the pinchcock. Measure the length of the thread either with a meter scale or, preferably, by a travelling microscope. Discharge the thread into a weighed vessel and weigh. Deduce the sectional area of the tube from the result, assuming the sp. gr. of mercury to be 13·6. The tube may be tested for uniformity of bore by measuring the length of the thread when it occupies different positions of the tube.

Comparison of Specific Gravities of two Liquids by balancing Columns of the Liquids (C)

31. *First Method*—only applicable in the case of liquids that do not mix.—Clamp a U tube with its limbs directed vertically upwards, and introduce the denser liquid until it rises to about one-third the full height in each limb. Pour the less dense liquid into one limb until it nearly reaches the top. The sp. grs. of the liquids are inversely as the vertical heights of their free surfaces above their common surface of separation. These heights will be most accurately obtained by measuring the height of each surface from the table by a meter scale, deducing the desired heights from the actual measurements.

There is no necessity for the limbs of the tube to be vertical so long as the heights are measured vertically. The experiment involves very important principles upon which the student should assure himself that he is clear.

32. *Second Method—Hare's Method.*—A long U tube is inverted with its limbs descending into two beakers containing the given liquids. Air is then drawn by suction from a tube leading from the bend of the U, this being closed by a pinchcock when the less dense liquid has risen nearly to the bend. The sp. grs. are inversely as the heights of the columns measured from the surfaces of the liquids in the two beakers. Consider why the method is more capable of general application than the first.

PRESSURE OF GASES

Method of reading Fortin's Standard Barometer (A)

33. Unless the barometer is in permanent adjustment in the laboratory, release the three screws in the ring immediately below it, allow it to hang freely and vertically, and clamp it by the screws in the position in which it hangs. Turn the screw at the bottom, which raises or depresses the wash-leather bottom of the mercury reservoir, until the surface of the mercury in the reservoir just touches the point of an ivory index that is seen just above it. If the surface is clean, the adjustment may be made very accurately by bringing the point into contact with its image reflected in the surface. Rack the vernier scale at the top to and fro, until, no matter how the eye is held, it is just impossible to see the white surface at the back between it and the mercury column. Note the method adopted to avoid parallax error in doing this. Read the vernier (Art. 9). For very refined work apply the correction for temperature supplied with the instrument.

The Verification of Boyle's Law (C)

34. THE LAW.—*Temperature remaining constant, the volume of a given mass of gas varies inversely with the pressure to which it is subjected;* or, more concisely, *temperature remaining constant, the product of the pressure and volume of a given mass of gas is a constant quantity.*

35. *First Method—for Pressures higher than that of the Atmosphere.*—The experiment may be carried out with a bent tube AB (Fig. 1), open at A, and closed at B. The tube is clamped in a laboratory stand with its limbs vertical.

Pour mercury into A so that the quantity CD introduced is rather more than sufficient to occupy the bend. The volume of the enclosed air is given by the length BD, and the pressure to which it is subjected, expressed in cms. of mercury, by the height of the mercury barometer in cms. added to the number of cms. by which the level of C exceeds that of D. It is impossible to obtain this last quantity with accuracy by direct measurement, and difficult to obtain the value of BD, and, instead of attempting to measure either directly, measure the heights of B, C, and D from the table, deducing BD and the vertical height from D to C from these measurements. Record the height of B once for all, as well as the height of the barometer, and enter the heights of C and D in the first two of a series of parallel columns. The pressure on the enclosed air is to be deduced from these observations and entered in the third column, the volume, also deduced, in the fourth, and the product of the pressure and the volume in the fifth.

Now, introduce more mercury, sufficient to cause C to rise about 15 cms., repeat the observations, and continue the process until the long limb of the tube is nearly full. The accuracy of the verification will appear in the approximation to constancy of the product entered in the last column of the table.

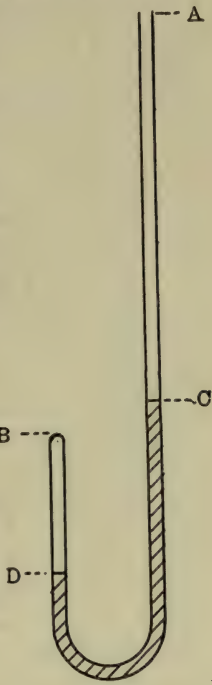

FIG. 1.

A correction may be introduced for the curvature of the closed end by subtracting from the height of the top of B the thickness of the glass + one-third of the internal radius of the tube. This value is based on the assumption that the closed end of the tube is hemispherical.

The details of an actual experiment carried out by the method described are given in Chapter X., p. 130.

36. *Second Method—for Pressures less than that of the Atmosphere.*—A convenient form of apparatus is shown in

Fig. 2. A U tube, open at A and closed by a stop-cock at B, is clamped in a laboratory stand. The second stop-cock F enables mercury to be discharged from the tube into a beaker placed below.

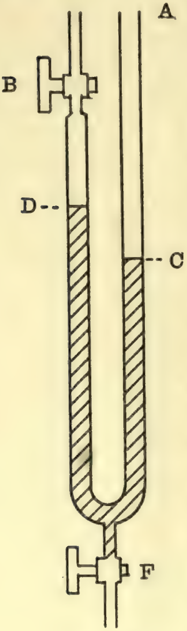

Fig. 2.

Close F, open B, and pour mercury into A until D is about 15 cms. below B. Then close B, measure the heights of B, D, and C from the table and also the height of the barometer. Record the results of the measurements in parallel columns as in the last experiment, deduce the pressure and the volume of the enclosed air and the pressure to which it was subjected; enter these in two other columns, and their product in a fifth. Next, open F, and allow mercury to escape until the level of D falls about 5 cms. C will fall more rapidly than D—consider why it should—so that the pressure on the enclosed gas becomes less than that of the atmosphere. Measure the heights of D and C from the table, deducing the volume and pressure as before, and continue the experiment, letting out more and more mercury by F until C descends to F. The degree of accuracy with which Boyle's Law is verified will appear, as before, in the approach to constancy of the product of the pressure and volume of the enclosed air.

CHAPTER IV

THE LAWS OF MOTION

Exercises with Atwood's Machine (C)

The machine is used to verify the following laws, which are included in Newton's Second Law of Motion.

37. (*a*) *The effect of a constant force acting on any mass is to impart to the mass a velocity that increases by equal amounts in equal times;* or, expressed more concisely, *a constant force acting on any mass develops in the mass a constant acceleration.*

To verify this, place equal masses on the two sides of the machine. They will, of course, balance. Were it not for friction, either mass, if given a slight downward start, would descend to the bottom with uniform speed, drawing up the other. Owing to unavoidable friction the masses will, however, soon come to rest; but the effect of friction may be nearly eliminated by adding a small excess, a piece of wire, for instance, to the descending mass, adjusting the excess until, on giving the mass a very slight downward impulse, it descends slowly and uniformly to the bottom. Now place an "*overweight*" in the form of a bar on this mass, and raise it to the top of the scale by lowering the mass on the other side. Start a metronome beating seconds near the machine, and release the system on a given beat. A good method to adopt is to hold the thread on the other side between the finger and thumb, releasing it on the beat. All mechanical releases, however ingenious, are objectionable. Adjust the ring and stage by repeated trial until the click caused by the catching of the overweight by the ring coincides with the second beat of the metronome, and the tap caused by the impact of the descending mass on the stage with the third. The distance between the ring and the stage gives the velocity acquired by the whole moving mass when acted on by the weight of the overweight for one second. Next, arrange for the overweight to be removed after two seconds, arranging the stage so that the descending mass strikes it in another second. The velocity acquired by the action of the overweight for two seconds is thus determined. Continue the experiment as far as the scale of the machine allows, and enter the results concisely in a table, the last column containing the values of velocity gained divided by time of action of the impressed force. According to the law stated, this should be constant.

38. *Second Method.*—It follows from simple mechanical considerations that the distance traversed from rest by a mass moving with constant acceleration is proportional to the square of the time, and, conversely, that, if the distance from rest is proportional to the square of the time, the acceleration is constant.

To make use of this principle, remove the ring, and find by trial the distance traversed in 1, 2, 3, . . . seconds from rest, the overweight remaining on the descending mass the whole time. Arrange the results in two columns, entering in a third the fraction $\frac{s}{t^2}$, s being the distance and t the time. For the law to be verified this ratio should be constant.

The actual value a of the acceleration is given by the relation $s=\frac{1}{2}at^2$. Hence $a=2\frac{s}{t^2}$. Find a from the mean value of $\frac{s}{t^2}$.

39. (*b*) *The acceleration developed by a force acting on any given mass is proportional to the force.*

Adjust equal masses on the two sides of the machine, adding a small excess to eliminate friction in the manner already described. Add an equal number of small and equal overweights to the two sides. Transfer one of these to the mass that is to descend, and, allowing the mass to descend through as large a distance as possible consistently with its blow upon the stage coinciding with a beat of the metronome, measure the time and distance traversed, deducing the acceleration as described in Art. 38. Transfer another overweight, repeat the experiment, deducing the acceleration in this case, and continue until all the overweights have been transferred. The total mass moved having remained unchanged by the transfer of the overweights from one side to the other, the ratio of the acceleration to the excess weight on the descending side should be constant. Enter the observed quantities and the deductions from them in tabular form, so as to show how far the constancy of this ratio is verified by the experiments.

40. (*c*) *The acting force remaining constant, the acceleration of a body acted on by a given force is inversely proportional to the mass of the body.*

The verification of this law is left as an exercise for the student. He is warned of the necessity for a correction for the mass of the pulley that may prove troublesome.

Determination of "g," the Acceleration of a Body falling freely under the Action of Gravity, by Atwood's Machine (C)

41. Proceeding as in Art. 38, determine the acceleration a produced by an overweight of mass m acting on two equal masses, each $= \mathrm{M}$. The values should be so chosen that the time of descent is about 5 or 6 seconds, and the descent should be as great as possible. Were it not for the mass of the pulley, the value of g would be given by the relation

$$g = \frac{2\mathrm{M} + m}{m} a.$$

To eliminate error due to the mass of the pulley, repeat the experiment with the same overweight, but with the masses M replaced by others much greater (M′). $M' = 3M$ is a convenient relation. The value of g is now accurately given by the relation

$$g = \frac{M' - M}{m} \times \frac{2aa'}{a - a'}$$

where a and a' are the accelerations in the first and second cases respectively. The value of g deduced in this manner cannot be regarded with any confidence.

The Isochronism of the Pendulum

42. The Principle.—*Whenever the motion of a body is such that it experiences a force of restitution towards a certain position, then if the restoring force is proportional to the displacement, the body oscillates about that position in equal times, no matter what is its amplitude of vibration on either side.* In the case of the pendulum this condition is not quite fulfilled, but it is very nearly fulfilled when the oscillations do not extend to more than a few degrees on either side of the vertical.

Construct a pendulum by hanging a lead bullet by a thread about 1 meter long from a support projecting from a wall. Make a vertical mark with chalk on the wall immediately behind, and draw, by the aid of a protractor, straight lines on the wall from the point of support of the pendulum, making angles of 10°, 20°, 30°, . . . with the vertical mark. Draw the pendulum aside through about 10° and release it, allowing it to oscillate. Take up a position in front of the pendulum, and observe by a watch the time taken to make a selected number, *e.g.* 50, complete oscillations to and fro. The time is taken most accurately from an instant at which the pendulum passes through its vertical position. Record the time, and estimate also as accurately as possible the amplitudes of swing on either side of the vertical at the beginning and at the end of the time observation. Enter the mean of these as the amplitude of oscillation.

Repeat the observations with different amplitudes, and express the results neatly. The period of oscillation should be found to increase, at first very slightly but afterwards more rapidly, as the amplitude increases. Plot the result as a graph in which amplitudes are plotted horizontally and periods of oscillation vertically.

Verification of the Law that the Period of Oscillation of a Simple Pendulum is proportional to the Square Root of its Length; and Determination of "g" (C)

43. The theory of the pendulum only assumes a very simple form when its mass is practically concentrated at a point. Such an ideal pendulum is known as a *simple pendulum.* The condition is approximately fulfilled in the case of a leaden bullet not more than 1 cm. in diameter suspended by a very fine thread not less than 50 cms. long.

Suspend such a pendulum from a support, and proceeding as in the last experiment, find the period of oscillation for oscillations of not more than 15° on either side of the vertical, and for different lengths of the pendulum. The length may be taken as the distance between the point of support and the centre of the bob, and it will facilitate subsequent calculation if the selected lengths are squares of natural numbers, *e.g.* 49, 64, 81, and 100 cms. Record the times occupied in performing a selected number of complete oscillations to and fro as in the last experiment, and deduce the period of a single oscillation for each selected length, recording the results in parallel columns, in the last of which enter the corresponding values of the ratio $\frac{T}{\sqrt{l}}$, T being the complete period and l the corresponding length of the pendulum. According to the law stated this ratio should be constant.

44. The period of oscillation of a simple pendulum is given by the relation $T = 2\pi\sqrt{\frac{l}{g}}$, so that $g = 4\pi^2\frac{l}{T^2}$. Calculate g from this equation, substituting for $\frac{l}{T^2}$ its value determined from the mean value of $\frac{T}{\sqrt{l}}$ deduced from the experiments.

The method is capable of far higher accuracy than that of Atwood's machine, but the value of g is most accurately determined by Kater's form of compound pendulum, the theory of which is not of an elementary character.

CHAPTER V

LIGHT

Verification of, and Exercises on, the Law of Reflection (C)

45. The Law.—Let PO (Fig. 3) represent a ray of light incident upon a reflecting surface intersecting the paper in AB. Let OS represent its reflected path, and ON the normal, or perpendicular, to the reflecting surface through O, the point of incidence. *Then the incident ray PO and the reflected ray OS always lie in the same plane with, but on opposite sides of, the normal ON, and the angle of incidence PON is equal to the angle of reflection NOS.*

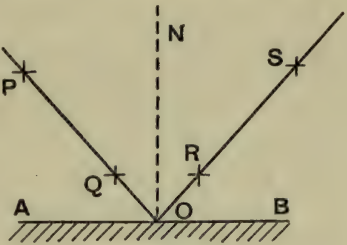

Fig. 3.

Verification. — Adjust a silvered glass mirror measuring about 20 cms. by 4 cms. on a sheet of paper on a horizontal board, with the reflecting surface vertical and its length horizontal. Trace on the paper the edge of the silvered face of the mirror AB (Fig. 3). Draw a straight line PQ to represent a ray making an angle of incidence PON of about 30°. Fix two pins as at P and Q on this line, one near the mirror, the other several inches from it. View the pins by reflection, adjusting the eye so that one appears to cover the other, and, keeping the eye in this position, fix two other pins as at R and S, so that these, seen directly, seem to be in line with the first pair seen by reflection. Withdraw the last pair, connecting their pricks in the paper by the straight line RS. This line represents the reflected ray. Produce the two rays to meet at O. Construct the normal ON. Measure PON and NOS, the angles of incidence and reflection, with a protractor, and record their values in two parallel columns with their difference in a third. Repeat with other rays, making angles of incidence of approximately 45° and 60°. The verification of the law appears in the approach to equality of corresponding angles of incidence and reflection.

Were it not for refraction of the rays by the glass, the point O would be situated on the silvered surface of the mirror. Owing to refraction, however, the rays should meet slightly in front of the silvered surface.

46. *Exercises.*—The student should first show that the following important propositions follow necessarily from the law of reflection, and he should then verify them by experiment, using the method of pin-sights as in the above experiment.

47. *If an incident ray, fixed in direction, falls on a plane mirror, the rotation of the mirror through any angle causes a rotation of the reflected ray through double that angle.*[1]

48. *A luminous point being situated in front of a plane mirror, rays proceeding from it and falling on the mirror diverge after reflection. The point from which they diverge is as far behind the mirror as the luminous point is in front of it,*[2]

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[1] The axis of rotation is assumed to be in the plane of the mirror and perpendicular to the incident ray.

[2] In the actual experiment, the point from which the reflected rays diverge is often found to be in a very different position from that indicated. The discrepancy is due to a slight curvature that exists in nearly all mirrors.

and is situated on the perpendicular from the given point when produced through the mirror.

49. When the courses of rays that originally proceed from a luminous point are so deflected that they either *diverge from* or *converge towards* another point, this second point is defined as an *image* of the first, which in its relation to the image is called the *object*. When, as in the above case, the deflected rays diverge from but do not actually pass through the image, the image is called *virtual*. When, however, as in cases to be subsequently studied, the deflected rays converge so as to actually pass through the image, it is said to be real.

Location of an Image by the Method of Parallax (B)

50. The method is very important. It may be illustrated in the case of a virtual image formed by a plane mirror in the following manner.

Fix a pin, that must be taller than the height of the mirror, in front of a plane mirror as in the preceding experiments. View the reflected image of the pin, and, holding a second long pin *behind* the mirror, place it in the position that the image of the first appears to occupy. The top of the second pin, seen over the top of the mirror, will then appear to be the continuation of the reflected image of the first. The accurate adjustment is effected by moving the eye continually from side to side while adjusting the second pin, and finding such a position for the pin, that, as the eye is moved, no relative displacement (*parallax*) appears between the second pin and the image. The guiding principle for all such parallax adjustments is, that, *when on moving the eye, relative displacement between two objects results, the one that appears to be displaced relatively to the other in the opposite direction to the movement of the eye is the nearer of the two.*

When, in this case, no parallactic displacement results from the movement of the eye, the second pin is fixed in the paper. It then occupies the actual position of the image of the first pin. Having found this position, remove the mirror, after having traced its edge on the paper, and find by measurement whether the position of the image as thus determined obeys the condition expressed in Art. 49.[1]

51. *Multiple Images formed by Reflection.*—Adjust two plane mirrors on a sheet of paper on a drawing-board so that the angle between them is 60°. Fix a long pin within the angle, but it is best to avoid placing it equally distant from the mirrors. On looking into the mirrors, five images of the pin will be seen. Locate the positions of all these by the method of parallax, using five long pins for the purpose. Trace the edges of the mirrors, and mark the positions of the images on the paper. Then remove mirrors and pins. Describe a circle with the point of intersection of the traces of the mirrors as centre with its circumference passing through the object. The circumference should also pass through the positions of all the images. Consider why this should be so.

Any other angle of inclination between the mirrors might have been selected, with a consequent difference in the number of images. When the angle is exactly contained in two right angles, the number of images is always one less than the number of times it is so contained.

Verification of the Law of Refraction (C)

52. The Law.—Let AB (Fig. 4) be the trace with the plane of the paper of a surface separating any two media, air and glass, for instance, and let PQ be a ray in the first medium, incident upon the separating surface at Q and refracted on entering the second medium into the direction QR. Let NQN′ be the normal to the surface of separation through the point of incidence Q. *Then the incident ray PQ and the refracted ray QR lie in the same plane with, but on opposite sides of, the normal, and, for the same two media, the sine of the angle of incidence PQN bears a constant ratio to the sine of the angle of refraction N′QR.*

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[1] See note 2, p. 30.

Definition.—*This constant ratio of the sines of the angles is defined as the index of refraction for light passing from the first medium into the other.* When one medium only is specified in stating the index of refraction, the ray is assumed to enter it from air, or, more accurately, from a vacuum.

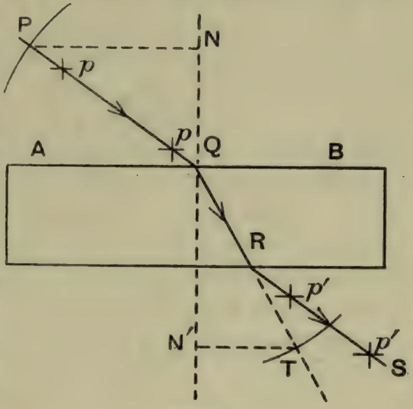

Fig. 4.

Verification of the Law.—Place a block of clear glass on a sheet of paper on a drawing-board. Trace its outline. Draw a straight line PQ to represent the course of an incident ray, and on this line fix two pins *pp*. Looking through the glass from the other side, adjust the eye so that the pins appear to be in line, and fix two other pins *p′p′* between the glass and the eye in such positions that they appear in line with the first pair as seen through the glass. The last pair of pins determines the course of the ray after it has traversed the glass. Trace RS the emergent ray, remove the glass, and complete the course of the ray by joining Q and R.

Deal only with the light as it is refracted into the glass at

Q, regarding PQ as the incident, and QR as the refracted, ray. Construct the normal NQN′. Measure the angles of incidence and refraction PQN and N′QR, and enter their values in the first two of a series of five parallel columns. In the third and fourth columns enter their sines, obtained from mathematical tables, and, in the fifth column, the ratio of the sines. Repeat the whole series of observations, selecting at least three different values for the angle of incidence. The verification of the law will appear in the approach to constancy of the ratio expressed in the last column. The mean of these may be taken as the index of refraction for light passing from air into the given specimen of glass.

53. With large values of the angle of incidence, and especially with optically dense glass, trouble may be experienced by the ill-defined and coloured images of the pins, these being due to the dispersion of white light into its constituent colours that accompanies refraction. The trouble may be avoided, either by performing the experiment in a room illuminated only by the monochromatic light of a sodium flame (Art. 97) or by using, instead of ordinary drawing paper, deep-red mat paper that is readily obtained from stationers.

54. *An Alternative Method.*—Instead of measuring the angles of incidence and refraction and referring to tables for their sines, a circle of not too small a radius may be drawn with Q, the point of incidence, as centre (Fig. 4), and perpendiculars PN and TN′ drawn to the normal from the points at which the circumference intersects the incident and refracted rays. It may be necessary to produce the refracted ray as in the figure. The ratio of these perpendiculars is, by elementary geometry, that of the sines of the angles of incidence and refraction, and, consequently, the lengths of the perpendiculars may be entered directly in two columns, and their ratio—the index of refraction—in a third.

Absence of a Definite Image formed by Refraction at a Plane Surface. Caustic by Refraction (C)

55. Place a thick glass block with clear vertical faces on a sheet of paper on a drawing-board, and fix a pin vertically at the middle of one side and in contact with the glass. Looking from the other side, trace, by the method of pin-sights, the courses of at least twenty rays from the object pin after their emergence from the glass, and represent them by straight lines ruled on the paper. Remove the glass after tracing its outline, and complete the courses of the rays, representing the courses of the rays within the glass by very faint lines. These last represent the incident rays radiating from the object pin, and the lines first drawn their paths after refraction into the air. Trace the backward directions of the refracted rays within the glass. It should now appear from the drawing (1) that the emergent rays do not, as in the case of reflection at a plane surface, diverge accurately from a common point, so that no definite image is formed in this case, but that, if the rays have been taken sufficiently close to one another, a cusped curve—caustic curve—is formed by the intersection of successive rays; (2) that, for rays of very nearly normal incidence, the refracted rays diverge so nearly from a common point that for these rays an image may be, without appreciable error, regarded as formed. This image is situated at the cusp of the caustic curve, and it may be shown that its distance from the surface is given by multiplying the distance of the object from the surface by the index of refraction. Assuming this, employ the diagram to deduce the index of refraction of the glass.

56. *Exercise.*—Place a plate of glass upon a printed page. Look straight down through the glass and notice that the print appears raised. Now look more and more obliquely, and notice that, the more oblique the vision, the more raised the print appears, until, when the vision is very oblique, the letters seem to be on the upper surface of the glass. Explain these appearances from the result of the preceding experiment.

57. *A Method for determining the Index of Refraction of a Transparent Block* (C).—Rule a short line on paper, and place over it a thick plate of glass, adjusting the glass so that the line terminates at one edge. Look straight down through the glass towards the end of the line, and adjust the point of a pin placed in contact with the side of the glass and immediately above the termination of the line, at such a height that, as tested by parallax, it coincides in position with the end of the line seen through the glass. The position of the pin indicates how much the image of the line is raised by refraction at the upper surface of the glass. Apply the law stated in Art. 55 to deduce the index of refraction.

Deviating Power and Minimum Deviation produced by a Prism (C)

58. The experiment should be performed by monochromatic light (Art. 53). From a point O on a sheet of paper on a drawing-board draw straight lines at intervals of 10°, from 0° to 90°. Adjust a glass prism with its triangular face on the paper, with an edge coinciding with the first line, and with the point O at approximately the centre of the edge. Do not move the prism before the completion of the following observations, as, unless the edge is very long, it is difficult to replace it accurately in the former position. Regarding the straight lines as representing rays incident on the prism, attempt to trace the course of each after transmission through it, by the method of pin-sights, representing the transmitted rays by straight lines ruled on the paper. Do not, however, trace the lines as far as the prism, as it is important to run no risk of disturbing it. A difficulty will probably be found with some of the rays owing to their total reflection within the prism. Do not concern yourself with these.

Mark the incident and the corresponding emergent rays with similar letters, remove the prism, and continue the incident and emergent rays to their points of intersection. Measure the angle through which each ray is deviated by its transmission through the prism, and tabulate the deviations and the corresponding angles of incidence. Notice that as the angle of incidence continually increases, the deviation at first decreases, but after reaching a minimum value—the angle of minimum deviation—it increases, and continues to increase for all further values of the angle of incidence. It will appear later that the measurement of the angle of minimum deviation supplies the most accurate means of measuring the index of refraction (Art. 60).

Minimum Deviation and Index of Refraction of a Prism. First Method (C)[1]

The index of refraction is deduced from two measurements.

59. *Measurement of the Angle of the Prism.*—If the edges of the triangular base that meet at the angle are not less than 10 cms. long, the angle may be determined with fair accuracy by tracing the base on paper and measuring the angle with a protractor. In any case, however, employ the following method, which is applicable however small the prism. The principle is employed in mineralogy for the measurement of the angles of a crystal.

Stand the prism on a sheet of paper on a drawing-board with the refracting edge directed towards a distant source of light, a candle flame at the further end of the room, for instance. Place the eye in such a position that the flame is seen by reflection in one face of the prism, and as near the edge as possible. The complete course of a ray now entering the eye is shown by CAE (Fig. 5), C being the position of the candle and E that of the eye. Fix the direction of this ray by two pins *pp*. Make a similar observation looking into the other face of the prism, locating A′E′, the reflected ray in this case, by the pins *p′p′*. Remove the prism without tracing its outline, and represent the reflected rays by straight lines, continuing them to intersect. Assuming that C is sufficiently distant, and A and A′ sufficiently close, for CA and CA′ to be sensibly parallel, the angle of the prism is one-half the angle between

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[1] This experiment may be regarded as an introduction to that of Arts. 95–97, where the same principle is employed, but in a manner that admits of far higher refinement.

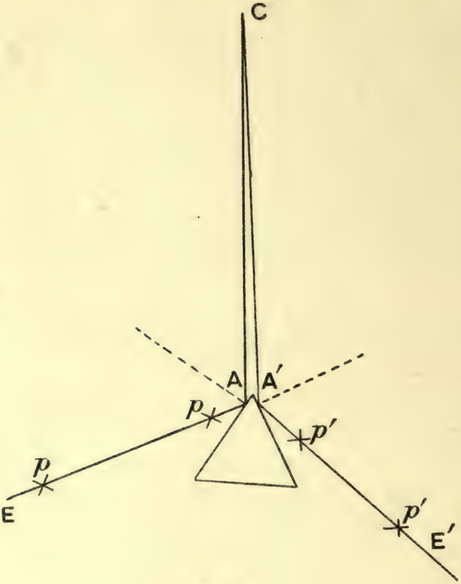

FIG. 5.

the reflected rays. Measure this angle with a protractor and deduce the angle of the prism.

60. *Measurement of the Angle of Minimum Deviation.*—Draw a straight line on the paper, locating its direction by two pins, and regard it as an incident ray. Place the prism at one end of this line, and, looking through it from the further side, adjust the eye so that the pins appear in line. On turning the prism in either direction, the pins will be relatively displaced, and the position of the eye must be readjusted for them to be again in line. Continue to turn the prism, first one way and then the other, always moving the eye to keep the pins in line, until a position is found in which the transmitted ray is nearest to the continuation of the incident ray. This becomes easy with a little practice, the line representing the incident rays seeming, when viewed through the prism, to swing into this position and then to retreat from it as the prism is turned continuously in the same direction. When the required condition is obtained, the deviation has its minimum value. Fix the emergent ray by pins, remove the pins and the prism, and measure the angle of minimum deviation.

It is shown in works on optics that if A denotes the angle of the prism, D the angle of minimum deviation, and μ the index of refraction,

$$\mu = \frac{\text{Sin}\ \frac{1}{2}(A + D)}{\text{Sin}\ \frac{1}{2}A}.$$

Deduce the index of refraction from this formula.

It should be noticed that both measurements assume that the prism is cut with its base at right angles to the refracting edge.

CONVEX LENSES

61. A *lens* is a block of some transparent substance bounded by curved—generally spherical—surfaces. The theory of lenses only assumes a simple form when the thickness of a lens is insignificant in comparison with the distances of the objects concerned and their images from it, and this condition will always be assumed in the following experiments. Such lenses are known as *simple lenses.*

Every lens that is thickest at the middle has a converging action upon a beam of light transmitted through it, and is known as a *converging*, or frequently as a *convex*, lens, although one of its surfaces may be concave; while all lenses that are thinnest at the middle have a *diverging* action on a transmitted beam, and are known as *diverging*, or as *concave*, lenses, though in such cases one surface may be convex.

The realisation of the following properties of lenses is of such vital importance while carrying out all experiments with them, that they are summarised here, although they would more appropriately appear in a work devoted to theoretical optics. The student should devote close attention to them before proceeding to the experiments, and should convince himself that he understands how they follow from elementary theory.

62. When a luminous object is situated at a great distance from a convex lens on its principal axis—the straight line through its centre that intersects its surfaces at right angles—its rays, after transmission through the lens, converge so as to form a real image on the further side. The point of intersection of this image with the principal axis is known as the *principal focus*, or, more briefly, as the *focus* of the lens, and its distance from the lens is known as the *focal length.* A second focus exists on the other side of the lens for light passing through it in the opposite direction, and the distances of the foci from the lens are equal. The image formed in this case is real, the rays actually passing through it (Art. 49), and it will form an actual picture of the object on a white screen held at the focus; or, if the rays are not intercepted by a screen, the image itself may be seen by an eye looking towards the lens from a point beyond and not so close that the distance between the image and the eye is less than the least distance of distinct vision—about 10 inches for normal sight.

So far, the object has been assumed to be at a very great distance from the lens. If it now approaches the lens, the image recedes on the further side, at first more slowly than the object approaches, and continues to do so, until, when the distance from the object to the lens is twice the focal length, the image is at this same distance, twice the focal length, on the further side. The distance between the object and its real image—four times the focal length—is now the least possible. On the further approach of the object the image recedes more rapidly than the object approaches, until, when the object reaches the focus, the image is at an infinite distance. As the object approaches the lens still farther, a real image becomes impossible, but a virtual image is formed behind the object, which may be seen on looking through the lens from the further side. The virtual image is first formed at a very great distance from the lens, but as the object continues to approach, the image moves up very rapidly, overtaking the object as it reaches the lens.

63. In all positions, and for all lenses, whether convex or concave, as well as for all spherical mirrors (Art. 88), if p represents the distance of the object, q that of the image, and f the distance of the focus, all distances being measured from the lens, a simple relation exists between these quantities that is expressed by the equation

$$\frac{1}{q} + \frac{1}{p} = \frac{1}{f}.$$

In applying this equation, p, q, and f are regarded as positive when rays proceed from the object on one side of the lens while the image and the focus are on the other. When any one of these quantities is situated on the other side of the lens to the side thus assumed, the equation still applies if the particular quantity is regarded as having a negative sign. Thus q is negative when the image is virtual, f is negative for a concave lens (Art. 82), and cases frequently occur in which rays incident on a lens, instead of diverging from a point on one side of the lens, are converging towards a point on the other. In such cases p would be negative.

64. *Relative Dimensions of Object and Image.*—It follows, from simple considerations, that the linear dimensions of an object and its image are proportional to their respective distances from the lens.

Images formed by Convex Lenses

65. Arrange a bright object, a gas flame, for instance, on one side of a convex lens at a considerable distance from it, and adjust a screen on the other side so that a sharply focussed picture of the object appears upon it. Note that the picture is inverted, and consider the reason for this. If the distance of the object from the lens is more than ten times that of the image, the image is very close to the focus of the lens. Do not attempt at present to measure the distances accurately, for fear of injuring the scale used by the flame. Remove the screen and look towards the lens from a distance of at least 10 inches beyond the position of the image, and the inverted image will be seen as a ghost apparently floating in space between the lens and the eye. Convince yourself that the image is actually nearer the eye than the lens by applying the method of parallax, moving the eye slightly from side to side, when the image will appear displaced relatively to the lens in the opposite direction to the motion of the eye (Art. 50). Test further by bringing the eye nearer the lens, when the image will become indistinct as it gets nearer to the eye than the least distance of distinct vision while the outline of the lens is still seen distinctly.

Replace the screen. Bring the object nearer the lens by a number of steps, focussing at each step, and notice the gradual retreat of the image. Notice also that the image increases in size (Art. 64). Notice that at a certain point the object and image are practically equidistant from the lens. The distance of each from the lens is now twice the focal length. As the object approaches still further, notice the rapid recession of the image. When a sharp focus is no longer possible, however distant the screen, look into the lens from the side remote from the object and observe the enlarged virtual image. Notice that this is erect, and consider the reason for it. Bring the object still nearer, until, when the eye is close to the lens, it experiences difficulty in seeing the image clearly. The image is now at the least distance of distinct vision. Verify that the object is still closer by removing the lens, when it will be quite impossible to see the object distinctly.

Verification of the Law $\frac{1}{q}+\frac{1}{p}=\frac{1}{f}$, and Rough Determination of the Focal Length of a Convex Lens (C)

66. *First Method—by the Formation of Image-Pictures on a Screen.*—Repeat the observations described in Art. 65 as regards real images, using, instead of the flame as object, a piece of wire gauze illuminated by a flame a short distance behind it. A more sharply defined image is obtained by the use of the gauze, and it is possible to measure the distance from the gauze to the lens with fair accuracy. Measure corresponding values of p, the distance of the object, and q, that of the image, from the lens, and in a third column, the value of f, the focal length, deduced from each pair of observations.

67. *Second Method—employing the Method of Parallax.*—Starting as before with the object at a considerable distance, repeat the above experiments, substituting a clamped pin for the screen. Look towards the lens from a considerable distance beyond it. The image of the gauze will be seen if the gauze itself and the eye are sufficiently removed from the lens. Bring the eye towards the lens as far as possible, consistently with the image being seen distinctly, and adjust the pin so that, as tested by the method of parallax, it is found to coincide in position with the image of the gauze. The position of the image is consequently determined. Record the distances of object and image, and deduce the value of f precisely as in the last experiment. Move the gauze nearer the lens by successive steps, determine the positions of the images as before, and deduce corresponding values of f.

68. In all these cases it is important to bear in mind that no real image is possible unless the object is further from the lens than the focal length.

Measurement of the Focal Length of a Convex Lens

69. *First Method* (B).—Adjust the wire gauze that serves as object at one end of an optical bench, and the screen at the other. Illuminate the gauze by a flame, employing monochromatic light when great accuracy is required (Art. 97). Fix the lens in a clamp that slides on the bench between the gauze and screen, and adjust the clamp by moving it to and fro until a sharply defined picture of the gauze appears on the screen. If with the gauze and screen at their furthest distance apart it is found impossible to obtain a sharply focussed image, either the bench is not long enough for the lens (Art. 68), or the curves of the lens are bad, in which case improvement will be effected by stopping the lens down so as only to use the central part.

A sharp picture being obtained, record the positions of the object, lens, and screen, as indicated on the scale of the bench, and deduce the values of p and q from these. Corrections will, however, almost certainly be necessary, owing to the impossibility of ensuring that the positions of the object, screen, and lens, as indicated upon the scale, shall correspond exactly with their actual positions. To apply the correction for p, select a glass rod about 10 cms. long, and measure its length accurately. Next, place the rod horizontally between the gauze and the lens, adjusting the position of the lens until it just touches both. The distance between the gauze and the lens is now the length of the rod, and the correction is obtained by comparing this with their distance apart, as indicated by the scale readings. The correction for q is obtained in a similar manner. It is better not to attempt to apply the correction that is obviously necessary for the thickness of the lens, as no simple rule applies, the simple theory, with which we are alone concerned, only holding with absolute accuracy for infinitely thin lenses.

Make a series of observations with the object and the screen at different distances apart. Arrange the records of the observations and their corrected values neatly, and deduce values of the focal length as before from corresponding values of p and q.

70. *Second Method* (A)—*employing the Method of Parallax* (B).—Proceed as in Art. 67, measuring the distances and applying corrections as in Art. 69. The experiment is illustrated on page 132.

71. *Third Method* (B).—Arrange the gauze and the screen at opposite ends of the optical bench, and focus the gauze on the screen by means of the lens. Move the screen nearer and nearer the lens by successive steps, focussing at each, until a position for the screen is found beyond which no sharply defined image is possible. The distance between the screen and the object is now four times the focal length of the lens (Art. 62).

72. *Fourth Method* (B).—Measure the length of an object, the distance of which from the lens should be fairly considerable. The distance between the bars of a distant window is often convenient. Fit the lens to a camera and direct it towards the object, so adjusting the camera that the principal axis of the lens approximately bisects the object at right angles. Measure the length of the image on the ground glass screen of the camera. Then if D is the distance between the object and the screen, l the length of the image, and L that of the object, the focal length is given by the relation

$$f = \frac{lL}{(l+L)^2} D,$$

which the student should verify for a simple lens.

This method is important, since, unlike the methods previously described, it is applicable not only to thin but to thick lenses, and also to combinations of lenses, if the distance of the object is very great compared with the thickness of the lens or combination.

72a. *Comparison of the Focal Lengths of Convex Lenses* (B).—This method is often of use for comparing the focal lengths of photographic lenses. It is applicable to thick as well as to thin lenses, as well as to all combinations of lenses that have a real focus.

Fit one of the lenses to a camera and direct it towards a very distant object. Focus accurately, and measure the length of the image. Repeat the experiment with another lens. The focal lengths of the lenses are proportional to the lengths of the images. The principle is extremely simple.

73. *Fifth Method* (C).—Place the lens on a plane mirror lying on the table with its reflecting surface uppermost. Adjust a pin held in a clamp above the lens and mirror, so that, as tested for parallax, the point of the pin coincides with its own image formed by reflection and the double transmission of light through the lens. In this position the pin is at the focus of the lens. The theory of the experiment should be verified.

Measurement of the Radii of Curvature of the Surfaces of a Lens (A)

74. The instrument used is the spherometer. Stand the spherometer on a sheet of plate glass, and adjust the central leg so that the instrument just rocks. The position of the central leg is given by the micrometer screw head. Next, place the spherometer on one surface of the lens, and again adjust the central leg to the rocking point. Deduce the depression or elevation of the central leg when placed on the spherical surface from the micrometer readings. Calling this d, the radius of curvature of the spherical surface is given by the relation

$$r = \frac{a^2}{6d} - \frac{d}{2}$$

where a is the distance between the points of any two of the outer legs.

75. The index of refraction of the substance of any thin lens, whether convex or concave, is given by the relation

$$\frac{1}{f} = (\mu - 1)\left(\frac{1}{r_1} + \frac{1}{r_2}\right)$$

r_1 and r_2 being the radii of curvature of the surfaces, both assumed convex outwards. If either is concave, the negative sign must be assigned to its radius.

Find the index of refraction of the given lens from this relation.

Measurement of the Magnifying Power of a Convex Lens when used as a Magnifying-Glass (C)

76. The magnifying power of any optical instrument is defined as the ratio of the angle subtended by the image viewed by means of the instrument to the angle subtended by the object when seen by the unaided eye to the greatest possible advantage. The object and image are assumed to be very small, or the definition fails to give a consistent value in every case.

77. Rule on a sheet of paper some 10 or 20 parallel lines a tenth of an inch apart. Bring the eye towards the paper until it is only just possible to see the lines clearly without undue strain. Now place a magnifying-glass—a convex lens of short focal length—upon the paper immediately opposite the eye, and, keeping the eye in the same position, bring the lens towards it until the lines as seen through the lens are on the point of becoming indistinct. Under this condition the magnifying-glass is being employed to the greatest practical advantage. Now, using both eyes, count how many tenth-inch spaces as seen through the lens by one eye coincide with one space as seen by the other eye directly. The number expresses the magnifying power. The theory of the method should be grasped.

78. The magnifying power of the lens when used in the above manner is theoretically given by the ratio of the least distance of distinct vision of the observer to the focal length of the lens. Obtain the magnifying power from this relation, and compare the result with that obtained by experiment.

The Principle of the Telescope

79. Fix a convex lens of long focal length—the object-glass of the telescope—in a lens holder, and direct it towards a distant object, a chimney, for instance. Fix a pin in a clamp and adjust it so that, as tested for parallax, the point of the pin coincides in position with the image of the distant object formed by the lens. Fix a lens of short focal length—the eyepiece of the telescope—in another holder, and using this as a magnifying-glass, adjust it so as to view the point of the pin to greatest advantage. On looking through the eyepiece, the image of the distant object should be seen intersected by the pin. The adjustment for parallax may now be completed with greater accuracy.

80. *Measurement of the Magnifying Power of a Telescope* (B).—Fix a vertical scale with horizontal divisions at equal distances of about 3 inches at the further end of the room, and focus the telescope upon it. Observe the scale with both eyes, one viewing it directly, and the other viewing it through the telescope, and count the number of divisions seen by the eye by the aid of the telescope that correspond with one division as seen directly. The number is the magnifying power.

81. The magnifying power is given theoretically by the ratio of the focal length of the object-glass to that of the eyepiece. Find it from this relation, and compare the result with that obtained by experiment.

CONCAVE LENSES

82. *Fundamental Properties of a Concave or Diverging Lens.*—When an object is situated at a very great distance from a concave lens upon its principal axis, the rays from it, after traversing the lens, diverge from a *virtual* image on the same side of the lens as the object. For an infinitely distant object the image is situated at the focus of the lens. As the object approaches the lens, so also does the image, but far more slowly, until the object overtakes the image at the surface of the lens. The equation given in Art. 63 is applicable to all concave lenses if a negative value is assigned to the focal length. Avoid the very common mistake of altering the signs in the general form of the equation given in Art. 63, but replace f by the numerical value of the focal length with the negative sign prefixed. Supposing, for instance, the focal length of a concave lens to be 12 cms., the value -12 is to be substituted for f in the equation.

83. *Experiments.*—Fix a concave lens in a lens holder, and arrange a source of light, a candle flame, for instance, at a considerable distance from it upon its principal axis. Verify by trial that it is impossible to form a picture of the object on a screen, no matter where the screen is placed. Look through the lens from the side remote from the object and observe the virtual image. Notice that this is erect. Consider why it should be so. Prove that the image is beyond the lens by placing the eye at such a distance from the lens that it is just impossible to focus its edge distinctly. The image, however, will appear quite distinct. Confirm by applying the test for parallax.

To distinguish between a Convex and a Concave Lens (B)

84. Look towards a distant object and pass the lens sideways in front of the eye. If, as viewed through the lens, the object appears to move in the direction of the movement of the lens, the lens is concave. If the image appears to move in the opposite direction, the lens is convex. The test is a very delicate one. It is of use in testing spectacle lenses of low power.

Measurement of the Focal Length of a Concave Lens

85. *First Method—employing the Method of Parallax* (C).—Clamp a pin—the object—at such a distance from the lens

that its image does not appear too small. Adjust a strip of plane mirror in contact with the lens on the side remote from the object, with its reflecting surface from, and so as to cover the lower half only, of the lens. Clamp a pin in front of the mirror. Looking towards the lens from the side remote from the object, the virtual image of the object will be seen, and also a virtual image of the second pin formed by reflection by the mirror. Move the second pin towards or from the mirror until its image in the mirror coincides in position, as tested for parallax, with the image of the first pin seen through the lens. The measurements and calculations necessary are left as an exercise for the student. Repeat the experiment with the object at different distances.

86. *Second Method* (B).—If a concave lens is placed in contact with a convex lens of shorter focal length, the diverging action of the concave lens will partly neutralise, but will not entirely destroy, the converging action of the convex lens, and the pair will form a combination acting as a single convex lens.

Select a suitable convex lens, and measure its focal length by any one of the methods described in Arts. 69, 70, and 71. Then, placing the given concave lens in contact with the convex lens in the same lens holder, measure the focal length of the combination. The focal length of the combination is then found from the relation

$$\frac{1}{F} = \frac{1}{f_1} + \frac{1}{f_2}$$

where f_1 and f_2 are the focal lengths of the two lenses, and F the focal length of the combination. The student should prove the relation from the equation of Art. 63.

Principle of the Telephoto Combination

87. Select a convex and a concave lens of not very different focal lengths. Fix the convex lens in a lens holder and focus a distant source of light on a screen. Now fix the concave lens in another lens holder, and place it in the course of the light just in front of the screen. Readjust the screen to obtain a sharp focus. The image will be slightly larger than before. Move the concave lens nearer the convex lens by successive small steps, focussing at each, and notice the continually increasing enlargement of the image.

The focal length of a combination of any two thin lenses is given by the relation

$$F = \frac{f_1 f_2}{(f_1 + f_2) - t}$$

where f_1 and f_2 are the focal lengths of the first and second lenses respectively traversed by the light, F that of the combination, and t the distance between them. Since, in the telephoto combination, f_2 is negative and nearly equal to f_1, it follows from the formula that as t decreases, F increases rapidly. Hence the magnification. The discussion of the formula scarcely comes within the range of elementary optics, but it is an instructive and easy exercise to trace the course of the rays in a given case by successive applications of the familiar geometrical construction for lenses and to show the resulting magnification.

The advantages of the combination are (1) that it enables the photographer to vary the size of the picture within wide limits without altering his position, and (2) that a long focal length, and consequently a large image, is obtained without the necessity for a correspondingly long camera.

Spherical Mirrors

88. The image-forming property of a concave spherical mirror is essentially similar to that of a convex lens, the difference being that the direction of the rays is reversed in the act of their deflection, from which it follows that images are real when on the same side of the mirror as the object, and virtual when on the remote side. With this qualification, every statement of Art. 62 applies to a concave mirror, and the Art. should be again read, and interpreted with reference to a concave mirror instead of a convex lens.

Similarly, it follows that the formula of Art. 63 applies to the case of a concave mirror, the convention of signs only demanding that the positive sign should be prefixed to all distances measured from the mirror in front of it, and the negative sign to distances measured from the mirror behind it.

The simple relation exists in the case of a spherical mirror that the focus is situated midway between the surface of the mirror and its centre of curvature. This relation has no counterpart in the case of a lens.

In experimenting with spherical mirrors, a difficulty is sometimes experienced from the fact that the screen receiving the image, or the head of the observer when in the proper position for viewing it, are liable to interfere with the direct course of incident rays. If this difficulty were obviated, every experiment that has been described for single lenses might be carried out equally well with spherical mirrors.

Measurement of the Radius of Curvature and Focal Length of a Concave Mirror

89. *First Method—by the Formation of a Luminous Image* (A).—Fix the mirror in a holder, and fix opposite it a card with a pin-hole at approximately the height of the centre of the mirror. Arrange a gas flame behind the card. Move the mirror towards and from the card, tilting it if necessary, until a sharp picture of the hole is formed close beside it on the card. The hole and its image are now at the centre of curvature of the mirror. The focus is midway between the hole and the surface of the mirror.

90. *By the Test for Parallax* (A).—Clamp a pin at a considerable distance in front of the mirror and look towards the mirror from a position beyond the pin. An inverted image of the pin should be seen between it and the mirror. An erect image would indicate that the image is virtual, the object being within the focal length, and in this case it should be moved further from the mirror. Applying the test for parallax, find whether the pin itself or its image is nearer the eye, and move the pin until, as tested for parallax, its point coincides in position with its own image. Both pin-point and image are now at the centre of curvature. Measure the distance of the point from the surface of the mirror. This distance is the radius of curvature. The focal length is half the distance. Both pin and image may finally be examined through a magnifying-glass and the adjustment for absence of parallax completed with greater accuracy.

91. *By the Spherometer* (A).—The measurement of the radius of curvature is effected exactly as described in Art. 74.

92. *Further Exercises.*—Continuing the experiment described in Art. 90, move the pin, already adjusted at the centre of curvature, slightly nearer the mirror. The image recedes from the mirror, approaching the observer. Adjust a second pin so that its point coincides with the image of the first. Notice that when this coincidence has been obtained, the first pin also coincides with the image of the second. Consider the meaning of this. Measure the distance of the first pin and that of its image as located by the second from the mirror, and deduce the focal length from the two distances. Continue the observations, moving the pin by successive small steps towards the mirror, and deduce a value for the focal length from each pair of measurements. Record the results neatly. Note that when the pin is nearer the mirror than the focus, the real image in front of the mirror is replaced by a virtual image behind.

Measurement of the Radius of Curvature and Focal Length of a Convex Mirror

93. Convex mirrors are related to concave lenses precisely as concave mirrors are related to convex lenses. For diverging incident light, consequently, the images are in every case virtual and situated between the mirror and its focus.

First Method—by the Spherometer (A).—This is the only satisfactory method. Proceed precisely as described in Art. 74. The focal length is half the radius of curvature.

94. *Employing the Test for Parallax* (C).—The method is essentially identical with that described for a concave lens in Art. 85. The details are left as an exercise for the student.

THE SPECTROMETER

Measurement of Index of Refraction by the Spectrometer (A)

The principle of this important measurement has already been described in Arts. 59 and 60. The substance of which the index of refraction is required is cut into the form of a prism with a refracting angle of about 60°, and with its refracting edge as nearly as possible perpendicular to the base. Two measurements are required: one, of the refracting angle, and another, of the minimum deviation experienced by a ray of given light traversing the prism. Before proceeding to these, some preliminary adjustments of the spectrometer are necessary.

95. *Adjustments of the Spectrometer.*—On looking into the eyepiece of the telescope, two crossed threads should be seen. If these do not appear sharply defined, adjust the

small tube that carries the lenses of the eyepiece until good definition of the threads is obtained without strain on the eye. Do not disturb this tube during the course of the experiment. The adjustment will vary with different observers. Next, open the window, and direct the telescope towards a distant object, the more distant the better, and, using the screw head, rack the tube that carries the eyepiece and threads until, on testing for parallax, no relative displacement appears between the image as seen in the telescope and the threads. The image formed by the object-glass is now in the actual plane of the threads, and the telescope is "adjusted for parallel rays." The racking screw is not to be disturbed during the rest of the experiment. Next, direct the telescope towards the length of the collimator. Open the slit at the farther end of the collimator, and place a lamp flame behind it. On looking into the telescope, the slit will appear as a fine line if the slit is narrow; if it appears broad, partially close the slit by its adjusting screw. Test the slit as seen through the telescope for parallax relatively to the crossed threads, and, if parallax appears, move the tube in the collimator that carries the slit until parallax disappears. The slit is now in at the focus of the collimator, and the rays between the collimator and the telescope are accurately parallel. The adjustment of the spectrometer is now complete.

96. *Measurement of the Refracting Angle of the Prism* (A).—Place the prism on its base upon the stage of the spectrometer, supporting its edges by pellets of soft wax unless the stage is supplied with levelling screws. The prism should be placed with its edge directed towards the collimator, and with its refracting faces, as nearly as can be judged by eye, equally inclined to it. Turn the telescope so as to observe the image of the slit by reflection in one of the faces of the prism. The slit is illuminated as in the previous adjustment, and so far there is no necessity for the light to be monochromatic. Estimate the height of the image in the field of view. Simple eye estimation is sufficiently accurate for this; then turn the telescope so that the image of the slit is seen by reflection in the other face of the prism. If it appears at the same height in the field of view, the refracting edge is parallel to the axis of the rotation of the telescope and all is well. If the heights are different, readjust the prism, either by the levelling screws of the stage, or by pressing a corner so as to compress the wax pellet, until, on repeating the observations, the required condition is obtained.

Now turn the telescope so that the slit seen by reflection in one face passes accurately through the intersection of the crossed threads. The final adjustment is effected by clamping the telescope and using the fine screw adjustment. Read the positions of the telescope on the graduated scale (for method of reading the vernier, see Art. 9). Next, turn the telescope to the other side and adjust it so that the slit, seen by reflection in the other face, is on the intersection of the threads. Read the position of the telescope in this position. The difference between the two readings gives the angle through which the telescope has been turned. One-half of this is the measure of the angle of the prism (Art. 59).

97. *Measurement of the Angle of Minimum Deviation.*—Either monochromatic light must be used for this measurement, or a source must be employed that gives a spectrum showing well-defined lines (Arts. 101 and 104). A ready means of obtaining yellow light that is very nearly monochromatic is to clamp a thick copper wire, the end of which has been coiled into a few turns of a spiral, and which has been rubbed into moist common salt, or, still better, sodium hydrate, in the flame of a Bunsen burner, the wire being about half an inch above the burner.

Illuminate the slit with the source of light, but if a flame is used do not bring it within a distance of six inches of the slit for fear of injuring the jaws. Turn the prism so that the rays from the collimator are incident upon and make an angle of about 30° with one face, and adjust the telescope so that the slit is seen by the rays deviated by transmission through the prism. Make the slit as fine as possible consistently with its being seen distinctly, then turn the prism and the telescope, always following the image with the telescope until a position of the prism is found, such that, no matter in which direction it is turned, the deviation increases. Leave the prism in this position, adjust the telescope so that the slit appears to cross the intersection of the threads, and read the position of the telescope. Next, remove the prism and turn the telescope so as to view the slit directly through the collimator. Read the position of the telescope, and deduce the angle of minimum deviation for the light used.

The index of refraction of the substance of the prism for the particular kind of light used is then deduced from the formula given in Art. 60.

Besides yellow sodium light, other kinds of light may be usefully employed, *e.g.* the three prominent red, green, and blue rays obtained by passing the discharge from an induction coil through rarefied hydrogen. The particular rays are defined by the lengths of their waves in the ether; it is upon these that their refrangibility and their position in the spectrum depends. A table of wave lengths for different kinds of light is given on p. 137.

The Projection of a Spectrum on a Screen

98. Use a powerful source, *e.g.* a limelight or an electric arc. The source is assumed to be fitted in a projection lantern. Place a metal plate containing a fine slit in the position commonly occupied by the lantern slide, focus the slit on the screen, and adjust its width. Place a prism immediately in front of the objective of the lantern, arranging it so that the incident light makes an angle of about 30° with the face on which it falls. A spectrum will now be seen, probably on a side wall. Turn the lantern and the stand that carries the prism so as to bring the spectrum on to the screen. Turn the prism to and fro until the position of minimum deviation is obtained.

The condition for least confusion due to overlapping of adjacent colours of the spectrum demands that the rays traversing the prism shall be parallel, as in Art. 95. This is not the case with the arrangement described here, but the method is sufficient for general purposes of demonstration.

The Spectroscope

99. The term *spectroscope* is properly used to indicate an instrument for observing a spectrum, the term *spectrometer* being applied when arrangements exist for making measurements on the spectrum. A spectrometer is, however, very generally termed a spectroscope.

Observations.—Adjust the spectrometer for minimum deviation for sodium light (Art. 97). The width of the slit should be adjusted according to the brightness of the light, the narrower the better, consistently with the image of the slit—the line in the spectrum—being seen easily. In the case of sodium light, it should be possible to narrow the slit sufficiently for the line to appear as a double, indicating that the light consists of two rays of slightly different refrangibilities.

100. *Continuous Spectrum.*—Replace the Bunsen flame by that of a lamp, and observe the continuous spectrum such as always appears when the source of light is incandescent solid or liquid matter, the incandescence in this case being that of particles of solid carbon. Any horizontal lines extending throughout the length of the spectrum are due either to irregularities, or specks of dust, in the slit. A few fine lines are of no account, but if more are visible, clean the slit by opening the jaws and rubbing the tapered end of a wooden match between them.

101. *Line Spectra.*—The light from an incandescent gas commonly consists of a finite number of rays of different refrangibilities. These, being separated to different degrees by the prism, yield a corresponding number of separate images of the slit—the lines of the spectrum. Two such lines have already been noticed as forming the spectrum of the incandescent vapour of sodium, since the common salt introduced into the flame is dissociated into sodium and chlorine, and the light emitted is almost entirely due to the sodium. Introduce compounds of other metals into the flame, using a platinum wire, cleaning the wire between each experiment by plunging it, while incandescent, into pure hydrochloric acid. Convenient metals to select are lithium, strontium, barium, and calcium. Measure the positions of the telescope when so adjusted that prominent lines cross the point of intersection of the crossed threads, and construct maps of various spectra. It will generally be sufficient to fill in the positions of fainter lines by eye. Also observe the spectra of rarefied gases when traversed by the discharge from an induction coil. Make maps of these spectra.

102. *Fluted Spectra.*—A line spectrum is always given by an incandescent gas when its temperature is sufficiently high and its pressure sufficiently low. Under other less simple conditions the spectrum may consist of a number of shaded *bands* or *flutings*. A fine example of a fluted spectrum is given by the light from the inner green cone of a Bunsen flame. To observe this it will generally be necessary to open the slit fairly wide. Introduce plenty of air into the flame, and place the burner close to the slit.

103. *Absorption Spectra.*—Arrange a source giving a continuous spectrum, a lamp frame, for instance, about six inches beyond the slit. Introduce a few grains of iodine into a test tube and heat in a Bunsen flame while holding the tube between the source of light and the slit. A number of dark lines will appear in the spectrum. These are due to the absorption of definite rays by the vapour of iodine. A beautiful example of an absorption spectrum is that produced by the red fumes given off when nitric acid is poured on to a few scraps of copper at the bottom of a test tube while air is present in the tube. Observe this. In these cases the absorption spectra are so complicated that it would be a very laborious affair to measure the position of every line, but a rough drawing should be made in each case.

Simpler absorption spectra, in which the shaded bands rather than lines appear, are given by many solutions, and are of great importance. Observe the absorption spectrum of a weak solution of potassium permanganate. Also that of blood.

104. *Fraunhofer Spectrum.* — Reflect sunlight into the spectroscope and observe the dark lines—first studied by Fraunhofer—that cross its length. They are due to the absorption of definite rays by gases in the atmosphere of the sun. Measure the positions of some of the most prominent and notice, from comparison with the results of former measurements (Art. 101), that some of them coincide in position with bright lines in the spectra of incandescent gases. The dark lines corresponding to the bright lines of hydrogen, and the double bright line of sodium, are specially definite in the solar spectrum.

Direct-Vision Spectroscope

105. For many purposes a spectrum may be observed with sufficient accuracy with a direct-vision spectroscope. The instrument is far more simple in use than the spectrometer assumed in the preceding articles, though the observations are naturally incapable of the same high degree of accuracy. The different spectra already described should be observed through a direct-vision spectroscope.

Photometry

106. *The luminous power or luminosity of a source of light is defined as the rate of emission of light in terms of that of a standard candle.* A standard candle is composed of spermaceti, with a rate of consumption of 120 grains per hour. Actual standard candles were formerly used in photometry, but are now replaced by pentane lamps.

Most measurements in photometry depend upon the fact that the illumination of a surface exposed normally to a source of light varies inversely with the square of its distance from the source.

107. *Comparison of the Luminous Powers of two Sources of Light by the Shadow Photometer* (B).—Clamp a rod, *e.g.* a pencil, an inch or so in front of a white screen, and adjust the sources at such distances from the screen that the two shadows of the rod are in contact and of equal shade. The luminous powers of the sources are directly as the squares of their distances from the screen. Prove this relation. Note that the position of the rod does not enter into the result.

108. *Comparison of the Luminous Powers of two Sources of Light by Bunsen's Photometer* (B).—The most accurate method for most purposes. Adjust the sources, one on each side of the screen, until the semi-transparent spot in the centre—formerly a spot of grease, but now made by placing a thin sheet of translucent paper between two pieces of card with central apertures—is either invisible, or appears of an equal slight shade as viewed from both sides. Absolute disappearance is rarely possible. The luminous powers of the sources are directly proportional to the squares of their distance from the screen. It is obviously of the utmost importance that extraneous light should be excluded in this department. Consider whether this condition is essential with the shadow photometer.

109. *Use of the Paraffin Block Photometer.*—The use of this photometer is left as an exercise for the student.

CHAPTER VI

HEAT

Determination of the Errors and Corrections of Thermometer Readings (A)

For the definition of the terms *error* and *correction,* see Art. 2. A centigrade thermometer is assumed.

110. *Correction for the Freezing-Point.*—Fill a funnel with pieces of crushed ice, allowing the water to drain into a beaker below, and immerse the thermometer in the ice so that, when the mercury has assumed a steady position, the top of the thread is just visible above the ice. Read carefully (Art. 5). The excess of the observed reading over 0° C. is the *correction* to be applied to the reading.

111. *Correction for the Boiling-Point.*—Use preferably the special form of thermometer boiler described in the text-books. In the absence of one, fit a 12-oz. flask with a cork through which two holes are bored, one for the thermometer and the other for a short tube for escaping steam. See that the first is such that the thermometer is firmly supported, but not so small that the fitting of the thermometer involves risk of breaking the instrument. Fill the flask to one-third of its capacity with water, insert the thermometer so that its bulb is above the water, and, if possible, so that the 100 degree mark shall appear just above the cork. This is very necessary, and it is in this adjustment that the chief advantage of the orthodox thermometer boiler appears. Boil the water briskly over a Bunsen flame, and take the reading of the top of the mercury thread when stationary. Read the barometer (Art. 33). If the barometric reading is exactly 76 cms., the temperature of the steam is 100° C. If the reading is other than 76 cms., apply a correction from the fact that, when near 100° C., the boiling-point rises at the rate of a degree for an increase of 2·7 cms. of the barometric height. Having found the boiling-point, deduce the correction for the observed reading of the thermometer.

112. Plot the two corrections on a graph in which readings of the thermometer are measured horizontally and their corresponding corrections vertically. It will be convenient to represent a degree on the vertical scale by 10 times the length adopted for a degree on the horizontal. Join the two points determined by a straight line. Assuming the bore of the thermometer to be uniform, the line indicates the correction for every reading of the thermometer.

Coefficient of Linear Expansion

113. The *coefficient of linear expansion* of a solid is defined as the increase in length of a rod of the solid that would measure 1 cm. at 0° C., when heated through a given degree of temperature. All solids expand so slightly with rise of temperature that the qualification "at 0° C." may be omitted in all except the most refined experiments.

Methods for determining the coefficient of linear expansion generally consist in measuring the length of a rod at one temperature, and the increase in length when the temperature is raised through a measured range. The methods of effecting these measurements are generally obvious from an examination of the particular apparatus employed.

Real and Apparent Expansion

114. The *coefficient of voluminal expansion*, or, more briefly, the *coefficient of expansion*, of any substance, whether solid, liquid, or gaseous, is defined as the increase in volume of a quantity that would measure 1 c.c. at 0° C., when heated through a degree of temperature. The coefficients of expansion of solids and liquids differ from one another and vary with temperature in no simple manner, though the variation with temperature is so slight that it may generally be ignored. The coefficients of expansion of all gases, however, excepting when near the conditions that determine liquefaction, are very nearly identical, and, when measured on the thermodynamic scale of temperature, are the same at all temperatures. The indications of a gas thermometer consequently agree with the thermodynamic scale of temperature.

115. The qualification "at 0° C." in the above definition may generally be omitted when dealing with solids, owing to their slight expansion with temperature. It is less safely omitted in the case of liquids, the expansion of which is generally considerably greater than that of solids, but it must on no account be omitted with gases, the expansion of which is very much greater.

116. The coefficient of expansion of a solid may be shown to be almost exactly three times the coefficient of linear expansion.

117. In most cases the expansions of liquids and gases are studied by observing their change of volume when contained in glass or other vessels. In such cases the result is modified by the expansion of the containing vessel, but it is often convenient to calculate first the coefficient of expansion on the assumption that the containing vessel itself does not expand. The coefficient thus determined is defined as the *coefficient of apparent expansion* in glass or other substance. The actual coefficient of expansion is then found by adding the coefficient of expansion of the vessel to the apparent coefficient. This operation, though not mathematically exact, involves so little error that it is practically justified.

Measurement of the Coefficient of Apparent Expansion of a Liquid

We shall assume that the liquid is contained in a glass vessel.

118. *Method of the Specific Gravity Bottle* (A).—Nearly fill a beaker that is sufficiently large to contain the bottle with the given liquid. The temperature should be rather higher than that of the air (Art. 18). Weigh the specific gravity bottle empty, then fill it by immersing it entirely in the liquid, and take the temperature by a thermometer with its bulb in the bottle. Withdraw the thermometer and insert the stopper, the neck only of the bottle being raised out of the liquid for the purpose. Then remove the bottle, wipe it and weigh, taking all precautions indicated in Art. 18. Empty the bottle back into the beaker, and, unless the liquid boils at a lower temperature, heat it to about 40° C. The heating is best effected in a large water bath. Regulate the source of heat so that the temperature becomes practically constant, then fill the bottle again, repeating the operations already described, and obtain the weight of the bottle together with its contents at the higher temperature.

If m is the mass of liquid contained at the lower temperature t, and m' that contained at the higher temperature t', the coefficient of apparent expansion referred to 0° C. and assumed uniform is given by the relation

$$a = \frac{m - m'}{m't' - mt}.$$

Omitting the qualification "0° C.," the value referred to 1 c.c. at the lower temperature is

$$a = \frac{m - m'}{m'(t' - t)}.$$

The student should prove these relations.

To obtain the true coefficient of expansion, add the coefficient of expansion of glass, which may be taken as 0·000027.

119. *Method of the Weight Thermometer* (A).—The principle is identical with that of the last experiment, but the method is of more general application.

Weigh the thermometer empty, and then fill with the given liquid. To do this, fix it in the clamp of a laboratory stand, and slightly heat it by a flame with its mouth below the surface of the liquid in a reservoir, *e.g.* an evaporating dish. The liquid should be previously heated so that there shall be no danger of the thermometer cracking as it enters; this is especially necessary with mercury. On allowing the thermometer to cool, a small quantity of liquid will enter. Boil this for a short time to expel the air, and again allow to cool. More liquid will now enter, this time nearly if not quite filling the thermometer. Repeat the boiling process, if necessary, until the thermometer is entirely filled with the liquid.

Keeping the mouth of the thermometer below the liquid, transfer it to a funnel filled with ice as in Art. 110. In 15 minutes the liquid may be assumed to have acquired the temperature of the melting ice and the reservoir may be removed. Wipe the neck of the thermometer, and transfer it either to a water bath, or, if 100° C. is selected as the higher temperature, to the thermometer boiler, as described in Art. 111. Before removing the thermometer from the ice, place a weighed crucible below the mouth, as liquid will discharge immediately the temperature rises, and the crucible is to be kept under the mouth until liquid has ceased to discharge at the higher temperature. The crucible may be supported by a wire triangle carried on a ring of the stand. If a water bath is used, the greatest care must be exercised in keeping the temperature steady. Weigh the crucible together with the discharged liquid, and, when cool, weigh the thermometer with the liquid remaining in it. The coefficient of apparent expansion is deduced from the relation given in Art. 119, and the true coefficient of expansion is found by the addition of the coefficient of expansion of glass.

120. *By the Dilatometer* (B).—The instrument consists of a bulb with a graduated stem. It is first necessary to find the volume of the bulb in terms of that of a division of the stem, and it is convenient to regard as the volume of the bulb not only that of the bulb itself, but, in addition, the volume of the part of the stem that is below the zero division.

First, find the volume of a division of the stem by the method of Art. 30, introducing the thread of mercury by slightly warming the bulb and then allowing it to cool with the mouth of the stem below the surface of mercury. To find the volume of the bulb, first weigh the dilatometer empty, and then nearly fill it with the given liquid by the method of Art. 119. The sp. gr. of the liquid must also be determined (Art. 18). The volume of the bulb in terms of a stem division is readily deduced from these measurements.

Immerse the instrument in melting ice, proceeding as in Art. 110. Express the volume at this temperature in terms of that of one stem division. Heat to different degrees in a water bath, or use the thermometer boiler, taking all suitable precautions, and take the readings of the dilatometer at each temperature. Deduce the coefficient of apparent expansion, and thence that of the real expansion of the liquid (Arts. 114 and 117).

The Expansion of Water

121. The volume of water changes in such an irregular manner as its temperature is raised, contracting from 0° to 4° C., and then expanding at a continually increasing rate as the temperature is farther raised, that no advantage is gained by applying the term coefficient of expansion to it, the law of its volume variation with temperature being most conveniently expressed by a table giving the volume of a gramme for every degree between 0° and 100° C. Data for the construction of such a table may be obtained by the method of Art. 118, and the application of this method is left as an exercise for the student; but the simpler method is that of the dilatometer (Art. 120). The experiments should be carried out in the manner already described, and a graph should be constructed from the results showing the relation of volumes, measured vertically, to temperatures, measured horizontally, between 0° and 100° C.

Measurement of the Coefficient of Expansion of Air at Constant Pressure (C)

122. In the following experiment the pressure on the gas does not remain absolutely constant, but allowance is made for its slight variation by the application of Boyle's Law.

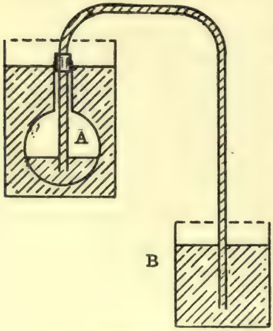

FIG. 6.

The apparatus suggested is represented in Fig. 6. A flask A, of about 150 c.c. capacity, is supported by a laboratory stand. It is provided with a well-fitting cork and a glass tube of small bore. One limb of the tube passes nearly to the bottom of the flask, the other, in the later stage of the experiment, terminating below the surface of water in the reservoir B. Dry the flask and weigh it. Introduce a few drops of sulphuric acid, just sufficient to wet the surface of the glass. This will effectively absorb any water vapour from the contained air. Fix the flask in position, bring a beaker or other convenient vessel from below, and adjust it so that the flask is completely enclosed. Fill this vessel with water and raise it to the boiling-point, boil for five minutes, and take the temperature of the boiling water with a thermometer, as the temperature of boiling water, though not that of the escaping steam, depends slightly on the nature of the containing vessel. During this process air will be expelled from the flask. Now place the reservoir B in position and remove the hot water. As the flask cools, water will pass into it from B. Reduce the flask to 0° C. by surrounding it with ice. After five minutes, remove first the cork and then the vessel containing the ice. Find the difference of height between the water levels in A and B by measuring each from the table, and read the barometer. Weigh the flask with the water it now contains, then fill with water up to the position previously occupied by the lower surface of the cork, and weigh again.

The volume of the air in the flask at 0° C. is deduced from the weighings. This air is, however, at less than atmospheric pressure, by reason of the fact that the levels of the water in A and B are different. Apply Boyle's Law to find the volume the air would occupy if brought to atmospheric pressure. Now, from the fact that this air, when raised to the boiling-point, occupies the whole of the flask, calculate its coefficient of expansion. The application of a slight correction, due to the fact that the air at 0° C. is saturated with water vapour, is left as an exercise. Data for the correction are supplied in Table III., p. 137.

Tap water may be used in place of melting ice, but in this case it is more important to allow for the cooled air being saturated with water vapour.

Measurement of the Coefficient of Increase of Pressure of a Constant Volume of Air with Rise of Temperature (A)

123. The above quantity is defined as the increase of pressure of a fixed volume of air consequent upon a rise of temperature of a degree, in terms of the pressure that the air would exert at 0° C. It follows from Boyle's Law that it is identical with the coefficient of expansion at constant pressure.

The apparatus, being of a standard pattern in use in all laboratories, need not be described.

Let the mercury well down in the open limb of the tube, and then immerse the bulb in melting ice. After a few minutes, raise the mercury by the particular means employed, so that it reaches in the closed limb a mark near the bulb. Read the height of the mercury in both limbs, and also the height of the barometer. Enter the height of the column in the open limb and the temperature of the bulb in parallel columns. Deduce, and enter in a third column, the pressure on the contained air.

Replace the ice by water, and raise the temperature of the water by successive steps of about 15 degrees until it boils. At each step bring the mercury back to the mark near the bulb, and read the height of the column in the open limb as well as the temperature of the water, being careful to keep the temperature constant for a few minutes before making any reading. Enter these quantities in the table, and deduce the pressure on the air in each case. On concluding the observations, and before removing the source of heat, let the mercury down to its lowest point, or it will enter the bulb during the process of cooling, and its subsequent extraction is troublesome.

From the quantities now entered find the increase in pressure for each increase in temperature, measured from

0° C., and deduce for each a value for the coefficient of increase of pressure.

Instead of using ice, the initial temperature may be obtained by the use of tap water at about the temperature of the air, and the resulting calculation, though slightly less simple, is quite easy. It is left as an exercise for the student.

The Accurate Use of the Thermometer

124. For an accurate record of temperature, it is essential that the whole of the thermometer as far as the end of the mercury thread shall be at the temperature of the substance tested. To observe the effect of the non-fulfilment of this condition, take the temperature of boiling water, first with the thermometer immersed as far as its 100° mark, and then with only the bulb immersed. If the stem is fairly free from the escaping steam, a difference of reading of over a degree will result.

It is frequently impossible to ensure that the stem of the thermometer shall be at the temperature of the substance tested. In such cases it is necessary to apply a correction if accuracy is essential.

Calorimetry

Measurement of the Specific Heat of a Metal by the Method of Mixtures (B)

125. *Definitions.*—The *unit of heat*, or *calorie*, is defined as the heat absorbed by a gramme of water as its temperature rises from 0° to 1° C. The *specific heat* of any substance is defined as the heat absorbed by a gramme of the substance as its temperature rises through one degree.[1]

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[1] This definition actually requires some modification owing to the possible inclusion of latent heat (Art. 129).

The specific heats of all substances vary slightly with temperature, but this variation is ignored in elementary study. The specific heat of water is of course 1.

If the specific heat s of a substance is assumed to be the same at all temperatures, it follows from the above definition that the heat absorbed by m grammes of a substance in rising through θ degrees is

$$H = ms\theta,$$

a relation that forms the foundation of most calculations in calorimetry.

126. In the *method of mixtures*, by which specific heats are generally determined, the given substance is first raised to a high temperature, and then immersed in water or some other liquid at a lower temperature, the specific heat being calculated from the rise of the temperature of the liquid.

A convenient form of heater for the metal is shown in Fig. 7, and consists of a copper tube A, 10 inches long and 1 inch in diameter, closed at the bottom, and fitted by a cork at its upper open end. It is attached to a wooden handle H. The metal, which is first weighed, is let down by a thread to the bottom of the heater, and the cork inserted, the thread remaining between the cork and the inside of the tube. The heater is then immersed in water boiling in a large copper vessel. The metal will assume the temperature of the water in about an hour. This temperature is taken by a thermometer in the water.

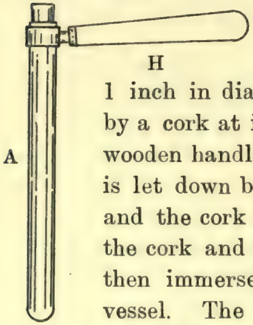

FIG. 7.

The *calorimeter* in which the mixture is to be effected consists of a copper vessel of about 150 c.c. capacity contained in a copper jacket of rather larger dimensions. It is separated from the jacket by standing on a layer of thick felt, and is wrapped round with loose cotton-wool. The calorimeter is weighed, first empty, and then about $\frac{4}{5}$ths full of water, and it is important that the temperature of this water should be a few degrees below that of the air. It is then placed in the jacket, and the water is carefully stirred with a thermometer, by which its temperature is then taken.

The metal is now to be transferred from the heater to the calorimeter with as little loss of heat as possible. To do this, temporarily remove the thermometer for fear of breaking it, and then, holding the tube by its wooden handle, remove it from the water and bring it near the calorimeter. There need be no undue hurry in this, as it will take several seconds for the contained metal to begin to cool appreciably. Now, grasping the cork, with the thread between it and the thumb, withdraw the cork and the metal with the same movement, and transfer the metal gently though swiftly to the calorimeter. With a little practice the time occupied in the transference need not exceed two seconds. On its immersion, do not allow the metal to touch either the side or the bottom of the calorimeter, or to become only partially immersed. Keep it in gentle movement for a minute, then allow it to rest on the bottom, replace the thermometer, use it for farther stirring and take the final temperature. Make sure that the temperature has ceased to rise by continuing to stir for a minute and observing the temperature again.

To find the specific heat, construct an equation in which the heat given out by the metal, expressed by the aid of the formula of Art. 125, is equated to the heat absorbed by the water and the calorimeter. An example of the method applied to an actual case is given on p. 131.

127. The principle involved in the calculation assumes that no heat other than that conveyed by the metal either enters or leaves the calorimeter between the readings of its

initial and final temperatures. This is, of course, not strictly true, since the calorimeter, if warmer than the surrounding air, imparts heat to it, and if cooler, receives heat from it. It is possible to apply corrections for both these sources of error, but the corrections are very small when care is taken that the temperature of the calorimeter at the beginning of the experiment is a few degrees lower than that of the air, and about the same number of degrees higher at the end, and also that the utmost range of its temperature is not more than six or eight degrees. These precautions are necessary in all calorimetric experiments. To measure so small a range with accuracy a sensitive thermometer is essential, and the thermometers employed in such experiments are commonly divided to tenths of a degree, hundredths being read by eye estimation.

It is, of course, necessary that the heating apparatus should not be so near the calorimeter as to affect it by radiation. The difficulty may be obviated by the use of screens.

Measurement of the Specific Heat of a Liquid (B)

128. The method is generally identical with that of the last experiment, the given liquid replacing the water, and a metal of previously determined specific heat being used. It may be necessary to select a metal on which the liquid exercises no chemical action, and, for the same reason, to use a calorimeter either of glass or of some metal other than copper.

Measurement of the Latent Heat of Liquefaction of Ice (B)

129. *Latent heat* is defined as the quantity of heat absorbed in effecting a physical change in one gramme of a substance without any consequent rise of temperature.

The two most important cases are the *latent heats of liquefaction and evaporation.* It follows from the definition, that if L denotes the latent heat of a specified physical change, and m the mass of the substance, the heat absorbed in effecting the change is mL. This expression used in conjunction with that of Art. 125 is generally sufficient for simple calculations on latent heat.

130. To measure the latent heat of liquefaction of ice, weigh a calorimeter, first empty and again when about $\frac{3}{4}$ths full of water. The temperature of the water will be reduced during the experiment; consequently, to minimise the effects of transference of heat between the calorimeter and surrounding air, its temperature at the beginning of the experiment should be rather higher than that of the air (Art. 127). A further advantage of warming the water arises from the more rapid melting of the ice on its introduction. Place the calorimeter in a jacket. Stir gently with the thermometer, and then, as a precaution, remove the thermometer during the introduction of the ice.

Select a piece of ice of about 10 grammes, but do not attempt to weigh it. Dry it thoroughly, first between the folds of a duster, then between several pieces of filter paper, and transfer it directly from the filter paper to the calorimeter. If a drop of water splashes over in this operation, recommence the experiment. Replace the thermometer instantly and stir continually until the ice is entirely melted. Take the final temperature, reweigh the calorimeter and its contents, and deduce the mass of the ice. From the expression given above and that of Art. 127, construct an equation in which the heat given out by the calorimeter and the contained water, in falling from its initial to its final temperature, is equated to the heat absorbed in melting the ice, and the heat absorbed by the water thus formed in rising from 0° C. to the final temperature. If the specific heat of the metal of the calorimeter is known, the latent heat of ice is the only unknown quantity in the equation, and it may be determined.

Measurement of the Latent Heat of Evaporation of Water at the Boiling-Point (C)

131. It is impossible to ensure an accurate result in this experiment without taking precautions that place it beyond the limits of elementary work.

Fill a conical flask with as large a base as possible to a depth of not more than an inch with water, and place fragments of a clay pipe in the water. The aim of both these precautions is to enable the water to boil as gently as possible, so that but little spray may be discharged into the steam by the bursting bubbles, such spray being a very serious cause of error. Fit a cork to the flask, and to the cork a glass tube that immediately turns at right angles and turns again vertically downwards at a distance of about a foot, its free end terminating during the experiment below the surface of water in a calorimeter. Protect the calorimeter from radiation from the flask by a screen, and avoid such fatal sources of error as "steam traps." Weigh the calorimeter, first empty and then $\frac{3}{4}$ths filled with water, as in previous experiments, and arrange, by the addition of ice if necessary, that the temperature of the water shall be about four degrees *below* that of the air. Record the temperature.

Now boil the water, and when steam is discharged freely from the tube, introduce the calorimeter from below, adjusting a stand to support it in its proper position with the end of the tube nearly reaching the bottom. Allow the steam to pass until the temperature of the water has risen about eight degrees. Remove the calorimeter, and weigh it again.

Deduce the mass of condensed steam. Construct a suitable equation, and determine the value of the latent heat as in the last experiment.

To find the Melting-Point of a Substance (A)

132. The substance is assumed to melt between the freezing and boiling points of water. Either paraffin wax or naphthalin may be used as an exercise, the latter having the advantage of a constant melting-point.

Draw out a glass tube in a flame so that the bore of the central part is of capillary dimensions. When the tube has cooled, introduce a piece of the substance into the wide part of the tube and melt it. It will at once pass to the finer part by capillary action. Seal off about 2 inches of the fine part and tie it to the bulb of a thermometer. Place the thermometer in a beaker of water and heat, continually stirring with the thermometer. When the melting-point of the substance is reached, it will suddenly become transparent. Do not record the temperature on noticing this, but remove the flame, and allow the water to cool until the substance again becomes opaque. Record the temperature when this change takes place. Then heat the water very gently, notice the temperature when the substance becomes transparent, and again allow the water to cool. Several readings of the melting and solidifying temperatures should be taken, and their mean regarded as the melting-point of the substance. Do not take the temperature of the first liquefaction, as temperature is then changing too rapidly for the indication to be reliable.

An Experiment on Cooling

133. Nearly fill a small metal cylinder or a test tube with paraffin wax, and melt this by immersing the tube in boiling water. Remove the tube, wipe it, and clamp it, preferably in the centre of a large jacket, otherwise in the open air but well removed from draughts and other disturbing influences. Insert a thermometer into the tube and record the temperature of the wax at intervals of a minute. The thermometer should be used as a stirrer until the wax solidifies. Continue the observations until the temperature of the wax has fallen to 30° C. Plot the result, and interpret the features of the graph, showing where the effect of latent heat appears.

Measurement of the Pressure of Saturated Water Vapour at Different Temperatures (C)

134. Use the apparatus represented in Fig. 6, p. 70. A well-fitting cork is essential. Add water to A so as to fill it to about one-third of its capacity, and insert the cork, adjusting the tube so as to terminate just above the surface of the water. Fill B half with water and half with mercury, and adjust it so that the tube dips below the water but not below the mercury. The difference of the levels of water in A and B must be at least 70 cms. Boil the water in A briskly, and continue the boiling until the water in B has become heated nearly to the boiling-point by the escaping steam. By this time all air will have been expelled from A. Remove the source of heat. As the vapour in A cools water will slowly enter from B. When the water in A has risen about half an inch above the end of the tube, raise B so that the end of the tube in it now dips below the surface of the mercury. On farther cooling, the mercury will rise in the tube and will attain a position of equilibrium depending on the temperature of A.

Adjust a beaker of water so as to enclose A, and raise the water to various temperatures, observing the corresponding positions of the top of the mercury column. Deduce the pressure on the vapour in each case. Record the results neatly, and express the variation of pressure with temperature by a graph. The method of deducing the pressure is left as an exercise for the student.

The Mechanical Equivalent of Heat

135. The direct measurement of this important quantity does not come within the province of these notes. The experiment described in Art. 181 may be regarded as supplying an indirect method for its determination, since the electrical equivalent of the energy that is transformed into heat is derived from purely mechanical considerations. The method, moreover, is capable of great accuracy, though it is probably inferior to the direct method in this respect.

CHAPTER VII

MAGNETISM

Experiments on Induction in the Earth's Field

136. Find the direction of the *magnetic* north by a compass needle. In future we shall speak of this direction simply as "north." Hold a poker horizontally with its point towards the north and tap it smartly several times with a hammer. The poker has now become a weak magnet. Verify this by bringing first the point and then the handle towards the compass needle, approaching in each case from either the E. or W. Notice that the end that was directed towards the N. has become a N. and the other a S. pole. Reverse the poker so that the handle now points N. Test. The point will probably still be a N. pole, though weaker than before. Give the poker a number of taps, beginning with very gentle ones, and test after each. Observe how the polarity of the poker first becomes weaker, and is then reversed, the end now directed N. becoming a N. pole. Interpret these results by the molecular theory of magnetism.

Instead of holding the poker horizontally, hold it, while still in the plane of the magnetic meridian, inclined to the horizontal at the angle of dip. Repeat the above experiments, and notice that the induced magnetisation is greater than in the previous cases.

Tracing the Lines of a Magnetic Field

137. *First Method—by a Small Compass Needle* (B).—Place a small bar magnet in the middle of a large sheet of drawing paper. The magnet should not be too strong, or the earth's magnetic influence, which introduces an interesting feature into the experiment, will not be apparent: a strip of steel magnetised by stroking it several times with either pole of a magnet answers well. Place the magnet in the first case so that its N. pole is directed towards the S. Trace the outline of the magnet on the paper, and do not disturb it during the experiment.

Place a small compass needle close to either pole of the magnet, and, when it has come to rest, mark the positions of its poles by pencil dots. Do not mistake the brass balancing bar that is often attached to the magnet for the magnet. Move the compass needle so that its nearer pole occupies the position of the dot that previously indicated the position of its outer pole. Record the new position of the outer pole by a dot, and continue in the same manner until the curved line traced by the needle either re-enters the magnet at its other pole or passes off the paper. Draw a line—a line of force—through the dots.

Map other lines of force. A dozen lines at least should be traced radiating from each pole of the magnet. Trace other lines, which are those of the earth's field, in any regions that may be left clear by the lines of the magnet. Make a careful study of the drawing and interpret it, marking the positions of any *neutral points.*

138. The drawing should be repeated (1) with the magnet still in the meridian but with its N. pole directed N., (2) with its N. pole directed either E. or W.

139. *Second Method—by Iron Filings* (B).—The method is simpler than the last, but can only be applied to very strong fields, such as that immediately surrounding a strong bar magnet. It is quite incapable of tracing the lines of the earth's field. Sprinkle iron filings lightly and uniformly over a sheet of card from a sieve held some three feet above.

The filings are best liberated from the sieve by gentle tapping. When the card appears of a uniform grey tint due to the filings upon it—the density of distribution that gives the best result can only be learnt by experience—lift the card carefully, and place it over the magnet. Support it so that its surface is horizontal throughout. Tap the card gently, and continue the tapping until the lines are clearly shown. Consider why the filings should set themselves in this manner.

As exercises on this method, trace the lines of (1) a bar magnet, (2) two bar magnets in line with opposite poles facing, (3) two magnets with similar poles facing. Consider the reason for the observed result in every case.

The Comparison of Magnetic Fields by the Oscillations of a Magnet (A)

140. Suspend a bar magnet in a stirrup by a bundle of unspun silk threads. The magnet should swing just over a sheet of card and should be enclosed by a glass shade. Allow the magnet to come to rest, and mark the direction of the magnetic meridian by a straight line on the card immediately under the central length of the magnet. Now displace the magnet through not more than 15° by another magnet from outside the shade, and then remove the disturbing magnet. The suspended magnet now oscillates according to a law identical with that of the pendulum, the time of its oscillation being inversely proportional to the square root of the strength of the field. Measure the time of a complete oscillation by a method precisely similar to that already described in Art. 42.

Repeat the observations at another place in the laboratory. The time will almost certainly be found to be appreciably different, by reason of iron in the building. Compare the magnetic fields at the two places from the law stated above. Attempt to explain the difference by reference to any iron pipes or girders known to be in the neighbourhood.

Comparison of the Moments of two Magnets (B)

141. The simple form of magnetometer will be assumed. It consists of a small magnet balanced at the centre of a large circular scale, the deflection being indicated by a light pointer fixed to the magnet. A long arm graduated in centimeters projects east and west of the instrument.

Adjust the magnetometer so that each end of the pointer indicates zero as nearly as possible. If the instrument is accurately constructed, the arm should now be at right angles to the magnetic meridian. Place one of the given magnets on the arm, and at such a distance as to produce a convenient deflection—one of from 15° to 20°. Record the deflection at both ends of the pointer. This precaution eliminates any error due to the geometrical axis of the pointer not passing through the centre of the graduated circle. Invert the magnet end for end, and again record the deflection, always reading both ends of the pointer. The inversion of the magnet will eliminate any small error resulting from the magnetic centre of the magnet not coinciding with its geometrical centre. Repeat the four observations with the deflecting magnet at the same distance on the other side of the magnetometer. This will eliminate small errors caused by the centre of the balanced magnet not corresponding with that of the projecting arm, and also by the arm not being accurately at right angles to the magnetic meridian. Take the mean of the eight readings that have now been recorded, and repeat the whole series with the other given magnet as a deflector.

When the length of the deflecting magnet is small compared with its distance from the balanced magnet, the deflection D is related to the moment of the deflecting magnet by the equation

$$\frac{M}{H}=\frac{r^3 \tan D}{2}$$

where M is the moment of the deflecting magnet, r the distance of its centre from that of the balanced magnet, and H the horizontal component of the earth's magnetic field; so that from the experiments with the two given magnets as deflectors

$$\frac{M}{M'}=\frac{\tan D}{\tan D'}.$$

The experiment is productive of but little edification unless the theory of these equations is understood, and at the best it is not very satisfactory in the simple form here given, as the assumption stated above, on which the formulæ depend, is rarely if ever fulfilled with sufficient accuracy. The difficulty is overcome by the introduction of certain corrections, but the theory of these does not enter into elementary work.

Measurements of the Moment of a Magnet and the Horizontal Component of the Earth's Magnetic Field (A)

142. An outline of these important measurements is given, though with some hesitation, as their theory involves principles that are beyond the limits of very elementary science. Two experiments are required.

(I.) *The Deflection Experiment.*—A bar magnet, about 10 cms. long, is selected, and employed to deflect the magnet of a magnetometer, precisely as in the last experiment, taking all the precautions that have been described. If D represents the mean of the eight readings of deflection, M the moment of the magnet used as deflector, r the distance of its centre from that of the magnetometer, and H the horizontal component of the earth's field,

$$\frac{M}{H}=\frac{r^3 \tan D}{2},$$

and consequently the ratio $\frac{M}{H}$ is determined.

(II.) *The Oscillation Experiment.*—The bar magnet used as deflector in the last experiment is now suspended by a bundle of unspun silk fibres, and the time of its complete oscillation to and fro determined as in Art. 140. It is shown by the principles of rigid dynamics that M and H are related to the time of oscillation T by the equation

$$MH=\frac{4\pi^2 K}{T^2}$$

where K is the *moment of inertia* of the magnet, moment of inertia being a quantity related to the rotation of a body as mass is related to its simple motion of translation. If the magnet is a rectangular bar of mass m, length l, and width c, its moment of inertia is $m \times \frac{l^2+c^2}{12}$; if it is cylindrical, the moment of inertia is $m \times \left(\frac{l^2}{12}+\frac{a^2}{4}\right)$, where a is its radius. Select the one of these quantities that applies, calculate K, and thence the product MH.

The ratio $\frac{M}{H}$ having been found by the first experiment, and the product MH by the second, it is a simple matter to deduce the values of both M and H.

In actual practice a far more refined apparatus is used than is assumed here, and various corrections are necessary that have not been noticed in this description.

CHAPTER VIII

ELECTRICITY

General Advice and Suggestions

143. (*a*) Before attaching wires to connecting screws, clean their ends by scraping with the blade of a knife, and, when attaching them to the screws, make sure that a good grip is effected. Trouble is often experienced owing to the faulty construction of the screws. Give the wire a good pull after connecting it, to be sure that a good grip has been made.

(*b*) When it is necessary to join the ends of two wires, never attempt to do so by merely twisting them together. Make the connection by proper screw terminals.

(*c*) Use all delicate apparatus, and indeed all apparatus, with care, and when it is necessary to move any instrument, lift and carry it gently.

(*d*) When using resistance boxes, first go over the plugs, and assure yourself that they are making good contact with the blocks between which they are inserted. The plugs are not to be wedged in with undue force; it should be sufficient if they make an appreciable grip. If this is not sufficient, either they, or the holes into which they fit, require cleaning.

(*e*) The needles of galvanometers often take a considerable time to come to rest if left to themselves, but they may, with a little practice, quickly be brought to rest by the aid of a weak magnet, the magnetised blade of a penknife, for instance.

(*f*) Be careful to keep all metal work away from battery acids and other liquids. If a drop of acid is spilt from a battery, wipe it up at once with a duster that should always be at hand.

(*g*) *Use of Resistance Boxes.*—The coils of the resistance boxes in common use are necessarily wound with fine wire, and they may consequently be destroyed by a strong current. To avoid danger of this, the boxes are never to be used in circuit with more than two Daniell's or Leclanché's cells in series, and they are on no account to be connected to an accumulator or to the mains. It is wise for a warning to this effect to be written clearly on a label permanently attached to the box.

144. Voltaic Cells.—Three voltaic cells are in general use: Daniell's cell, Leclanché's cell, and the accumulator.

Daniell's cell is particularly suited for experiments that require a very steady though not a strong current, since, owing to its freedom from polarization, its electromotive force (E.M.F.) is not appreciably affected by the current. Since, however, its two liquids mix slowly and the zinc dissolves even when no current is passing, a Daniell's cell should only be fitted up immediately before use, and taken to pieces immediately after. For this purpose, the cells should be kept near a sink, to which they should be taken after use, and the zincs withdrawn and rinsed in tap water. Do not withdraw the zincs except near the sink, and avoid the objectionable practices of putting the zincs, wet with acid, on the laboratory table, or of balancing them on the tops of the porous pots, from which they straightway fall.

Leclanché's cell has a higher E.M.F. than Daniell's, as well as, size for size, a lower resistance. It is consequently capable of developing a stronger current, while it has the further advantage that no chemical or other action occurs within it except during the actual passage of a current.

Leclanché's cells may consequently be left permanently charged. They experience, however, serious though temporary polarization when supplying a current, so that they are useless when constancy in the current is essential. They are largely used for electrical testing.

The *accumulator* has a higher E.M.F. than either of the above cells, as well as, size for size, a far lower resistance. In the absence of a direct supply from the mains, a battery of accumulators is always used when a strong and steady current is required. If, however, accumulators are either short-circuited or connected to a circuit of low resistance, the current supplied may be so great as to injure the cells themselves. A very safe rule is never to use such a current that would discharge the accumulator in less than one-tenth of its complete time of discharge. Thus, the current drawn from a 20 ampere-hour (20 A.H.) accumulator should not exceed 2 amperes, and so on. When, however, the current is only required for a short time, such as a minute or so, this limit may be safely exceeded, especially when the cells are fully charged. The damage to an accumulator resulting from the passage of too strong a current is so great, that it is a good plan to connect the cells of a battery of accumulators by lead wire that fuses when the current exceeds a certain value, in place of the thick copper wire commonly used. For a 20 A.H. accumulator a lead wire fusing at 5 amperes may be used.

Electrical Units

145. The experiments that follow are concerned with the measurements of *current*, *resistance*, *potential difference*, and *electrical power*. The units of these quantities have been selected so as to conform with the absolute C.G.S. system of measurement (Art. 3), but for practical purposes they are defined in the following manner.

The *ampere*, the unit of current, is the current that flowing through a solution of nitrate of silver in water deposits silver at the rate of 0·001118 gramme per sec.

The *ohm*, the unit of electrical resistance, is the resistance at 0° C. of a uniform thread of mercury 106·3 cms. long and of mass 14·4521 grammes.

The *volt*, the unit of potential difference and of electromotive force, is the potential difference that applied to the ends of a conductor of resistance 1 ohm will maintain in the conductor a steady current of 1 ampere.

146. Apart from the question of units, the quantities *current* and *potential difference* have been so defined that their product is proportional to the rate of doing electrical work in driving the current, a quantity known as *electrical power*. Further, the units themselves have been so selected that the product of current, in amperes, and potential difference, in volts, expresses the electrical power in *watts*, and when multiplied by 10^7 expresses it in *ergs per sec.* Thus, the electrical power of a current of C amperes, driven by a potential difference of V volts, is VC watts, or $VC \times 10^7$ ergs per sec.

To distinguish between the Poles of a Cell or Battery (B)

147. (*a*) *First Method—by the Deflection of a Compass Needle.*—Connect the poles of the cell or battery by a long copper wire, but bear in mind the danger of short-circuiting in the case of accumulators (Art. 143), and hold the wire above a compass needle, and parallel to it when undeflected. Notice the direction in which the needle is deflected, and apply the rule that if the right hand be held close to the wire, with the palm presented towards the needle and the fingers in the direction of the current, the N. pole of the needle is urged in the direction of the thumb.

(*b*) *Second Method—by the Formation of an Electromagnet.*—Wind a dozen turns or so of insulated wire connecting the poles round an iron rod, *e.g.* the rod of a retort stand. The rod becomes a magnet, and its polarity may be tested by a compass needle. Do this, and apply the rule, deduced from the one given above, that the end of the rod round which the current circulates in the direction of the motion of the hands of a clock is the S. pole. Deduce the rule.

(*c*) *Third Method—by the Electrolysis of Potassium Iodide.*—Attach two wires to the terminals and bring their bare ends on to a piece of filter paper moistened with a solution of potassium iodide. A brown colouration, due to liberation of iodine, appears round the wire connected to the + pole. The method is not applicable to a cell of lower E.M.F. than one volt, since a higher E.M.F. is required to urge a current through the solution (Art. 172).

To determine which of two Cells has the higher E.M.F. (B)

148. A Daniell's cell and a Leclanché's cell may be used. Arrange the cells *in series*, the + terminal of one being connected to the – terminal of the other (Fig. 9, A, p. 97), and join the free terminals by a long piece of insulated copper wire. Hold the wire over a compass needle as in Art. 147, and notice the direction in which the needle is deflected. Now invert the connections of one cell and repeat the observation, noticing whether the inversion of the cell has merely diminished the deflection, or whether it has reversed its direction. Deduce which cell has the higher E.M.F. from the result.

If the E.M.F.'s of the cells are nearly equal, the compass needle may show no appreciable deflection in the second case. In such a case, arrange a sensitive galvanometer in circuit with the cells instead of using the compass needle. The circuit should also include a make and break key.

A Study of Polarization

149. Arrange two Leclanché's cells in series, but so as to act in opposition, *i.e.* with one pair of similar terminals connected, and connect the free terminals through a sensitive galvanometer, a make and break key being also included in the circuit. On completing the circuit, a slight deflection of the galvanometer needle will probably result. Now, break the circuit, and short-circuit one cell by connecting its terminals by a short copper wire for a minute. Immediately reconnect through the galvanometer. A large deflection will now follow, as the E.M.F. of the cell that was short-circuited has been greatly decreased by polarization. Leave the circuit completed, and observe the gradual decrease in the deflection, due to the recovery of the cell. The effects of short-circuiting for different periods of time may be studied.

Repeat the experiment, using a pair of Daniell's cells in place of the Leclanché's.

The Electromotive Force of a Cell is independent of its Size

150. Compare the E.M.F.'s of two Daniell's cells that differ in size by the method of Art. 148, using a sensitive galvanometer. No appreciable deflection will be observed, any slight current that might result being due to differences of chemical composition.

The Detection and Measurement of Electric Currents

151. Methods used for the measurement of electric currents may be divided into two classes:—

(*a*) *Absolute methods*, in which the measurement of the current is given directly, and does not depend upon a previous comparison between the instrument used and some other current-measuring instrument. The only instrument of this class used in elementary work is the tangent galvanometer. In most cases, however, the tangent galvanometer is merely used to *compare* two currents, and such comparison may be effected simply and with fair accuracy. The absolute measurement of currents by the tangent galvanometer involves additional magnetic observations (indicated in Art. 142) of such refinement, and frequently of uncertainty, that it is rarely attempted.

(*b*) *Derived methods,* in which the value of the current is deduced by the aid of data previously derived by absolute methods. These methods are almost always employed in practice. They are illustrated in the important class of current-measuring instruments known as ammeters, and an excellent illustration is supplied by the experiment described in Arts. 158–9, which supplies the most accurate method of measuring a steady current.

In addition to these instruments, *sensitive galvanometers* are largely employed in the laboratory, their use being either to detect small currents or to effect a rough comparison between them. The principle originally applied in their action was that of the deflection of a suspended magnet by an electric current, and this is still employed in the most sensitive instruments. For most purposes, however, such galvanometers have now been almost entirely replaced by instruments in which the current is detected by the deflection of a coil suspended between the poles of a magnet. These *suspended coil galvanometers* are nearly as sensitive, and are far more convenient in use than the older instruments.

On the Use of the Tangent Galvanometer

152. *The Principle.*—When the needle of a galvanometer is very small compared with the coils, and when these are so arranged that the magnetic field of the current, in the neighbourhood of the needle, is at right angles to the horizontal component of the earth's field, the current is proportional to the tangent of the angle through which it deflects the needle. This relation is very simple and the principle should be understood. A galvanometer in which the above conditions are fulfilled is known as a *tangent galvanometer*.

Use of the Galvanometer.—To use a tangent galvanometer, first adjust it by the levelling screws so that the base is horizontal, then turn it so that the reading of each end of the pointer is as nearly as possible zero. If the galvanometer is accurately constructed, the coils will now be parallel to the magnetic meridian, and the magnetic force due the current in them will be, in the neighbourhood of the needle, at right angles to the meridian; but to correct for error due to this condition not having been fulfilled with absolute accuracy, reverse the current in the coils after having read the deflection from both ends of the pointer, and again read the deflection at each end. The mean of the four readings is to be taken as the *deflection*. For the necessity for reading the position at both ends of the pointer, see Art. 141.

It follows from simple considerations that, for accuracy of measurement, the deflection should neither be too large nor too small, a deflection of 45° being the best. Tangent galvanometers are generally provided with several coils of different numbers of turns of wire, and that coil should be selected that gives if possible a deflection that lies between 30° and 60°. If, with the fewest turns of wire, the deflection exceeds 60°, the galvanometer may sometimes be shunted with advantage, by bridging its terminals by a piece of German silver wire.

The Measurement of the Resistance of a Cell (C)

153. Connect the galvanometer in circuit with a resistance box and a Daniell's cell, the galvanometer being connected through the commutator K (Fig. 8). Adjust the galvanometer (Art. 152), and complete the circuit. If, with the fewest number of galvanometer turns, the deflection exceeds 60°, introduce resistance in the box to reduce it to below 60°. Record the deflection, taking the mean of four readings. Now increase the box resistance so as to approximately halve the deflection, and record the new value of the deflection.

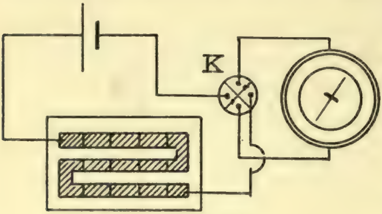

FIG. 8.

Then if R_1 and R_2 denote the resistances in the box in the two cases, X the combined resistances of the galvanometer, cell, and connecting wires, and E the E.M.F. of the cell, the currents C_1 and C_2 are given by

$$\frac{E}{R_1+X}=C_1, \text{ and } \frac{E}{R_2+X}=C_2,$$

from which, by division,

$$\frac{R_2+X}{R_1+X}=\frac{C_1}{C_2}=\frac{\tan D_1}{\tan D_2},$$

D_1 and D_2 being the angles of deflection in the two cases. From this

$$X=\frac{R_2 \tan D_2 - R_1 \tan D_1}{\tan D_1 - \tan D_2}.$$

The value of X is to be determined from this equation. If the resistances of the galvanometer and connecting wires are known, that of the cell at once follows. The experiment is illustrated by an example on p. 133.

The experiment is of little profit unless the theory indicated above is understood.

Consider why the method would be unreliable if applied to a Leclanché's cell.

Arrangement of Cells "in Series" and "in Parallel"

154. Connect a Daniell's cell with a tangent galvanometer, a resistance box being included in the circuit. Start with no resistance in the box, reducing the sensitiveness of the galvanometer, if necessary, by the addition of a shunt between its terminals (Art. 152). Record the deflection as the mean of four readings (Art. 152).

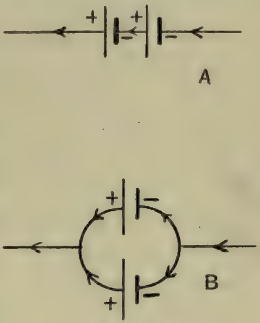

FIG. 9.
A, cells "in series."
B, cells "in parallel."

Repeat the observations with a second Daniell's cell in place of the first.

Cells in Series.—Now, arrange the two cells "in series" (Fig. 9, A). Repeat the observations with the "battery" thus formed. Refer to mathematical tables for the tangents of the mean angles of deflection in the various cases. These, being proportional to the respective currents, may be regarded as measures of the currents in arbitrary units. Note as the result of the observations that the current given by the two cells in series through a circuit of low resistance is scarcely greater than that given by a single cell. Consider the reason for this.

Now, however, add considerable resistance to the circuit. The resistance should be so high that a convenient deflection is obtained when using the highest number of galvanometer turns, and the shunt should, of course, be removed. Repeat the whole series of observations, and notice that the current in this case is nearly double that given by a single cell.

Cells in Parallel.—Arrange the cells "in parallel" (Fig. 9, B) and repeat the observations. Notice that in this case the current given by the cells in a circuit of low resistance is nearly double that given by one cell, but that when the resistance of the circuit is high, little advantage is gained by the addition of the second cell.

The theory of these important results is very simple, and should be clearly understood.

The Comparison of the Electromotive Forces of two Cells by the "Sum and Difference Method" (C)

155. Neither of the cells should be affected by polarization. An accumulator and a Daniell's cell are suitable.

Connect the cells in series through a tangent galvanometer and an adjustable resistance. Use the highest number of turns the galvanometer allows, and obtain a convenient deflection by adjustment of the resistance. Record the deflection as in the preceding experiments. Invert the connections of one cell, as in Art. 148, noticing after doing so whether the deflection is merely decreased or whether it is reversed in direction. Determine from this which cell has the higher E.M.F. Again record the deflection. Then if E_1 is the E.M.F. of the cell of higher, and E_2 the E.M.F. of the cell of lower E.M.F., and R the total resistance of the circuit in the two cases, the currents C_1 and C_2 are

$$\frac{E_1 + E_2}{R} = C_1 \text{ and } \frac{E_1 - E_2}{R} = C_2,$$

from which, by division,

$$\frac{E_1 + E_2}{E_1 - E_2} = \frac{C_1}{C_2} = \frac{\tan D_1}{\tan D_2}$$

where D_1 and D_2 are the angles of deflection.
Hence

$$\frac{E_1}{E_2} = \frac{\tan D_1 + \tan D_2}{\tan D_1 - \tan D_2}.$$

Find the ratio $\frac{E_1}{E_2}$ from this relation, and assuming the E.M.F. of the Daniell's cell to be 1·10 volts, calculate that of the other.

If a Leclanché's cell were used in this experiment, the result would be affected by its polarization. Consider whether the effect of polarization would result in the calculated value of the E.M.F. of the Leclanché's cell being too high or too low.

The Absolute Measure of Electric Currents by the Tangent Galvanometer

156. The actual measure of the current traversing the coils of a tangent galvanometer is given by the expression

$$C = Ha \tan D$$

where H is the horizontal component of the earth's magnetic field, D the angle of deflection, and a a quantity known as the *factor of the galvanometer*, its value being determined by the dimensions of the coils, the number of turns of wire they contain, and their position relatively to the suspended magnet. If the galvanometer is so constructed that all these quantities admit of exact measurement, a may be determined directly. Thus, for a galvanometer consisting of a coil of n turns of mean radius r, with the magnet in the centre,

$$a=\frac{5r}{\pi n}$$

for the current to be given in *amperes*.

In Helmholtz's more perfect form of tangent galvanometer, in which two coils, each consisting of $\frac{1}{2}n$ turns of wire of mean radius r, are separated by a mean distance equal to the mean radius of either,

$$a=\frac{25\sqrt{5}r}{8\pi n}.$$

If the factor of a tangent galvanometer does not admit of determination by direct measurement, it may be found by indirect methods. That described in Art. 159a is probably the best of these.

The determination of H has been discussed in Art. 142. Owing to the fact that H not only varies from hour to hour under normal conditions, but that its value is profoundly modified by neighbouring masses of iron such as are employed in the construction of most buildings, the tangent galvanometer is rarely used for the absolute measure of currents. We shall assume, however, that H is known with sufficient accuracy for the galvanometer to be employed in this manner in the next two experiments, which are introduced merely as illustrations.

The Measurement of the Electromotive Force of a Cell (C)

157. The experiment is essentially the same as that already described in Art. 153. In this case, however, instead of working with a circuit of low resistance, an essential condition for the accurate measurement of the resistance of the cell, it is better to make the resistance of the circuit high, to reduce possible trouble owing to polarization. Hence, the highest number of galvanometer turns should be used, and the current reduced so as to bring the deflection within convenient limits by addition of resistance in the box. After making the two sets of observations described in Art. 153, and deducing the value of X from them, E, the E.M.F. of the cell, is given by the equation

$$E = (R_1 + X)C_1$$

where $$C_1 = Ha \tan D_1.$$

As R_1 will be much greater than X, it is not necessary to know X with great accuracy. E is given in volts.

Determination of the Electro-chemical Equivalent of Copper (B)

158. The *electro-chemical equivalent* of an element is defined as the mass of that element liberated at an electrode of an electrolytic cell by the transmission of a coulomb of electricity through one of its compounds, a coulomb being the quantity of electricity transmitted by the passage of an ampere for one second. Consequently, if e denotes the electro-chemical equivalent of the element, C the current, and t the time in seconds, the mass liberated is

$$m = eCt.$$

We shall assume copper to be used, though the highest accuracy is possible with silver. The electrolytic cell or voltameter is filled with a slightly acidified solution of sulphate of copper, the electrodes consist of two plates of copper, and m is determined by weighing the cathode—the plate at which the current leaves the solution—before and after the experiment.

Arrange in a single circuit a pair of accumulators in series, a copper voltameter, a rheostat, and a tangent galvanometer, the last, as always, through a commutator. Complete the circuit by the commutator, adjust the rheostat, and select the number of galvanometer turns so as to obtain suitable values for the current and deflection. From 1 to 2 amperes is a convenient strength for the current. Break the circuit.

Now, clean the cathode in water, then rinse in spirit and dry, well above the top of a Bunsen flame. Weigh the plate. Replace, and complete the circuit, noting by a watch the instant of doing so. Allow the current to flow for about twenty minutes, taking the time accurately, and reading the galvanometer deflection with the current alternately direct and reversed at equal intervals of time. At the conclusion of the experiment, remove the cathode, clean and weigh it as before, and deduce the mass of deposited copper. Find the current corresponding to the mean galvanometer deflection, and thence determine the value of the electro-chemical equivalent.

159. The experiment has been described as conducted for the determination of an electro-chemical equivalent. The electro-chemical equivalents of the metals are, however, so accurately known, having been determined once for all by special experiments arranged and conducted with the greatest possible care and refinement, that it is more usually adopted in practice for the measurement of a current, and it supplies the most accurate method known of making such measurement. In such cases, silver is generally used in preference to copper, the electro-chemical equivalent of silver being ·001118 gramme per coulomb (Art. 145).

To test the Readings of an Ammeter

159a. Electric currents are generally measured in practice by instruments known as *ammeters* (measures of amperes).

Different principles are employed in their construction, which are, unfortunately, not often obvious from their examination. The testing of an ammeter may conveniently be effected by two experiments.

(i.) *To test whether the Currents traversing an Ammeter are proportional to their indicated Values.*—Arrange the ammeter in series with a battery of accumulators, a rheostat, and a tangent galvanometer. Obtain various currents, extending through the range of the ammeter, by adjustment with the rheostat, and take readings as nearly simultaneously as possible on the ammeter and galvanometer. The ammeter readings should be proportional to the tangents of the angles of deflection of the galvanometer. Test whether this is so, arranging the observations and results concisely.

(ii.) *To compare the actual Value of any one Current with its Value as indicated by the Ammeter.*—Employ the method of Arts. 158, 159. The arrangement of the details is left as an exercise for the student.

By combining the results of the above experiments, it becomes possible to construct a graph giving the actual correction to be added to every reading of the ammeter to give the true value of the current. This also is left as an exercise.

Sensitive Galvanometers

160. For the current traversing the cells of a galvanometer to be proportional to the tangent of the angle of inflection, it is essential that the distances of the coils from the needle shall be large compared with the length of the needle. This condition is, however, fatal to sensitiveness, and, in so-called *sensitive galvanometers*, it is completely ignored, the wire being wound in small coils, and as closely to the needle as possible. There is, in consequence, no simple relation between the current and deflection in such instruments. The relation may, however, be determined by experiment in various ways; its experimental determination is known as the *calibration* of a galvanometer.

Calibration of a Sensitive Galvanometer

161. *First Method* (B).—Connect the sensitive galvanometer in series with a tangent galvanometer and a Daniell's cell. The tangent galvanometer should be made as sensitive as possible by using its highest number of turns of wire, and it will probably be necessary to shunt the sensitive galvanometer by connecting its terminals by a wire of low resistance. If it is required to reduce the results to absolute measure, but not otherwise, it will be necessary to know the resistances of the galvanometer and its shunt. The commutator may be arranged to reverse the currents in both galvanometers simultaneously, and care must be taken that the galvanometers are so far apart that the needle of neither is directly affected by the current flowing through the coils of the other. It is easy to devise a test for this.

Obtain different currents, by adjusting the rheostat, so that readings are obtained throughout the entire range of the sensitive galvanometer, and read the corresponding deflections on both galvanometers. Record the observations neatly, and construct a graph, plotting the deflections of the sensitive galvanometers horizontally, and the tangents of the corresponding deflections of the tangent galvanometer vertically. The graph will indicate directly the law according to which the current traversing the coils of the sensitive galvanometer increases with the deflection, and it should be preserved for future use with the particular galvanometer, since it will be possible, by the aid of the graph, to use the sensitive galvanometer for the comparison of currents.

It will probably appear that for some 15° or 20° from the zero, the graph is sensibly a straight line. While this condition is fulfilled, the currents are practically proportional to the angles of deflection.

162. If the value in amperes of any one current in the sensitive galvanometer is known, the vertical scale of the graph may be expressed in amperes, or more conveniently in micro-amperes (millionths of an ampere). To arrive at this, select a current that gives deflections that can be accurately read on both galvanometers, calculate the value of the current in the tangent galvanometer from its deflection, and thence determine the current in the sensitive galvanometer, using the relation that if C denotes the current in the tangent galvanometer, G the resistance of the sensitive galvanometer, and S that of its shunt, the current in the sensitive galvanometer is given by

$$C' = \frac{S}{G+S}C.$$

The proof of the formula is simple. A far simpler and generally more accurate method of arriving at the same result is, however, given in the next Art.

163. *Second Method* (B). — Arrange the galvanometer, through a commutator, in circuit with a Daniell's cell and a resistance box, and adjust the galvanometer (Art. 152). Begin with the highest resistance the box allows, 12,000 ohms probably, and complete the circuit by the commutator. If the resulting deflection is more than 10°, as will probably be the case, the galvanometer must be shunted, but not so as to reduce the deflection much below 10°. Record the deflection from the mean of four readings, and enter it in a table, together with the box resistance. Decrease the box resistance by such steps as shall cause the deflection to increase by approximately equal steps of

10°, entering corresponding values of deflections and box resistance at each step.

Calculate the currents in the circuit, expressing them in micro-amperes (millionths of an ampere), by dividing the E.M.F. of the cell, which may be taken as 1·10 volts, by the total resistance of the circuit. The combined resistances of the cell, shunted galvanometer, and connecting wires will probably form so small a fraction of the resistance in the box in every case, that it will generally be safe to regard the resistance in the box alone as that of the circuit. Calculate in each case the current in the galvanometer by the application of the formula of Art. 162, and construct a graph, plotting deflections horizontally and corresponding currents in the galvanometer vertically. Read the latter part of Art. 161 with reference to the graph.

Measurement of the Sensitiveness of a Galvanometer (B)

164. The *sensitiveness of a galvanometer* may be roughly indicated by stating the number of *units of deflection* resulting from the passage of a current of a micro-ampere, the *unit of deflection* being regarded as the smallest deflection capable of ready and certain detection, and it will depend, of course, upon the particular means of indicating the deflection that may be employed. The student must judge for himself the value to be assigned to the unit in any given case.

To determine the sensitiveness of a galvanometer as defined in this way, first decide on the value to be assigned to the unit, and then proceed as in Art. 163, passing a small current through the galvanometer and recording the deflection. The current selected should not be too small, but should not be beyond the limit at which the deflection ceases to be proportional to the current

(Art. 161, end). The sensitiveness is at once determined from these observations.

THE MEASUREMENT OF ELECTRICAL RESISTANCE

Measurement of Resistance by the Method of Substitution (C)

165. Arrange a given wire in series with a Daniell's cell and a galvanometer of any form. Shunt the galvanometer if necessary so as to obtain a convenient deflection, and record the deflection. Little is gained in this case by taking readings with the current reversed.

Now replace the wire by a resistance box, and introduce such resistance in the box that the former deflection is reproduced as nearly as possible. If it is possible to effect this exactly, the resistance now in the box is obviously that of the wire. It will, however, generally be found that one value of the box resistance gives a deflection slightly higher, and the next a deflection slightly lower, than that formerly obtained. When this is the case, calculate by proportion (interpolation) the value of the intermediate resistance that would give the former deflection, and regard this as the resistance of the wire. Consider what assumptions are made in the process of interpolation, and how far they are justified.

Measurement of Resistance by the Wheatstone's Sliding Bridge (B)

166. The principle on which Wheatstone's Bridge depends is illustrated in Fig. 10, in which a current C is assumed to divide at A into two branches which subsequently reunite at B. Two points, D and F, on the branches are connected through a galvanometer G. Let P, Q, R, and S represent the resistances of the wires against which they are placed. Then it is easy to show that if $\frac{P}{Q}=\frac{R}{S}$, no current will flow through the bridge DF, and, conversely, that if there is no current in the bridge the relation $\frac{P}{Q}=\frac{R}{S}$ must exist.

The actual arrangement adopted in the "sliding bridge" is shown in Fig. 11, in which the letters correspond with those of Fig. 10. The shaded parts are copper strips of inappreciable resistance. L is a Leclanché cell connected to A and to the "slider" B. The slider carries a spring contact, by which, when an observation is required, actual contact is made for a moment with the graduated platinoid wire NZ. G is a sensitive galvanometer, P is the wire the resistance of which is required, and Q is a standard resistance.

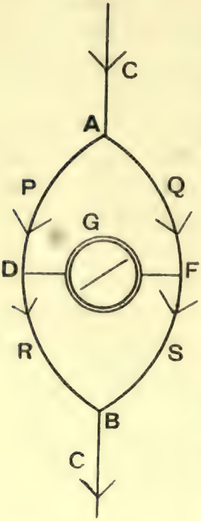

FIG. 10.

Fit up the apparatus as shown, and test whether all is right by making contact at B, first with the slider almost at the extreme left, and then almost at the extreme right of the scale. The resulting galvanometer deflections should be in opposite directions. Then find the position of B that gives no deflection and read off the lengths NB and BZ. Then, from the principle enunciated, and assuming the wire NZ to be of uniform section,

$$\frac{P}{Q}=\frac{NB}{BZ},$$

from which P is determined in terms of the standard Q.

P and Q are now to be interchanged, a second value of P found by repeating the experiment, and the mean of the two values taken.

Both P and Q must be connected to the bridge by thick copper wires of inappreciable resistance, or the resistance of the connecting wires must be allowed for.

167. For accurate work with the sliding bridge, it is necessary to add a correction to the scale reading of B taken from the left, to allow for the impossibility of ensuring that, when B is at the zero of the scale, there shall be no resistance between D and the point at which B makes contact with the graduated wire. This may be called the zero correction. Having thus found the corrected length to the left of B, that on the right is found by subtracting this from the complete "electrical length" of the graduated wire, the electrical length being the resistance between D and F, measured by way of the wire in terms of that of scale division. The zero correction and the electrical length of the wire should be known for every sliding bridge. Their determination forms the subject of the next experiment.

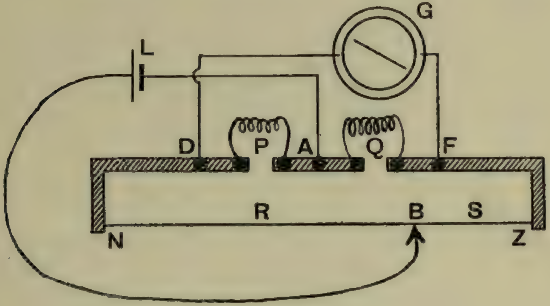

FIG. 11.

The Corrections of the Sliding Bridge (A)

167a. Repeat the last experiment, using for P and Q two coils the resistances of which are in a known and fairly high ratio, a 10 ohm and a 1 ohm coil, for instance. Let d_1 be the scale reading of the slider when P is in the left-hand gap, and d_2 the scale reading with P in the right. Also let L be the electrical length of the wire, and a the zero correction. The two balanced positions give the equations

$$\frac{\mathrm{P}}{\mathrm{Q}}=\frac{a+d_1}{\mathrm{L}-(a+d_1)} \text{ and } \frac{\mathrm{Q}}{\mathrm{P}}=\frac{a+d_2}{\mathrm{L}-(a+d_2)},$$

from which the two unknown quantities L and a are determined, their values being

$$\mathrm{L}=\frac{\mathrm{P}+\mathrm{Q}}{\mathrm{P}-\mathrm{Q}}(d_1-d_2) \text{ and } a=\frac{\mathrm{PL}}{\mathrm{P}+\mathrm{Q}}-d_1.$$

It should be noticed that the wire is assumed to be uniform. For accurate work, however, no such assumption must be made, but the wire must be "calibrated" throughout by a method that cannot be included in these notes.

Measurement of the Difference between the Resistances of two Coils of very nearly equal Resistance

168. Arrange the coils in the two gaps of the sliding bridge outside D and F in Fig. 11 (p. 109), but not shown in the figure, and use for P and Q two coils of equal or nearly equal resistance. It is not necessary to know their value. Adjust for no galvanometer deflection, and record the scale reading of the slider. Now, interchange the coils and repeat the observation. The difference between the resistances of the coils is the resistance of the bridge wire between the two scale readings. This may be found by proportion if the resistance of the entire wire is known, and this last may be found by measurement with another sliding bridge or by the method of Art. 169.

The principle involved is fairly obvious.

Measurement of Resistance by the Post Office Box (A)

169. The method of Art. 166 only admits of fair accuracy if the resistances compared are low and not very different, and it is rarely used. The same principle, that of Wheatstone's Bridge, as applied in the Post Office Box, is of far wider application.

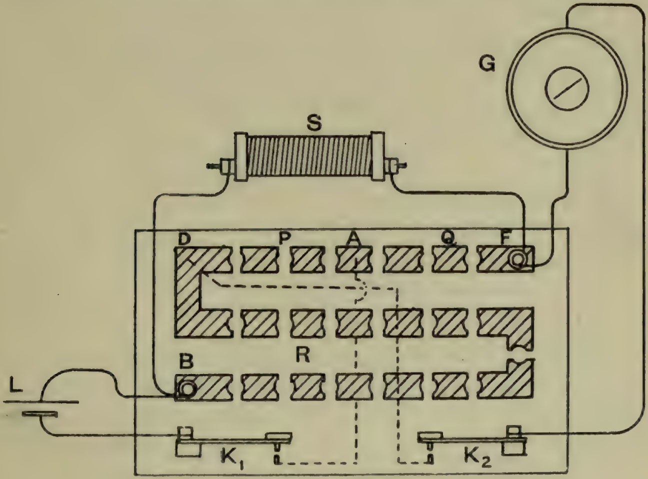

FIG. 12.

The arrangement of the coils in the "box" is shown in Fig. 12, where the letters correspond with those of the explanatory diagram in Fig. 10, and the two diagrams should be studied together. The "balance arms" P and Q each contain coils of 10, 100, and 1000 ohms, any of which may be used. R consists of a number of coils in series by which any number of ohms between 1 and 10,000 may be introduced, and S is the coil of unknown resistance. The battery is connected directly to B, and through a spring key K_1, which is permanently fitted to the box, to A. The galvanometer is connected, directly to F, and, through the key K_2, to D. It is convenient if R includes an "infinity plug" which simply breaks the circuit.

Having made all connections as shown, begin with 100 ohms in each of the arms P and Q. Test whether all is well by depressing the keys for an instant, first with no resistance, and then with a very high resistance, preferably the infinity resistance, in R, when deflections in opposite directions should result. The battery should always be connected before, and disconnected after, the galvanometer.[1] The preliminary test having proved satisfactory, find the resistance in R that gives as nearly as possible no deflection in the galvanometer. If an exact balance is found possible, then, since $\frac{P}{Q}=\frac{R}{S}$ (Art. 166), and $P=Q$, R is a measure of S, the unknown resistance. Generally, however, it will not be possible to obtain an exact balance, a deflection in one direction resulting from one value of R, and a deflection in the other direction following when R is increased by one ohm, the smallest resistance commonly supplied in the box. In this, and indeed in every case, repeat the experiment, using for P/Q the highest ratio that will enable a balance to be obtained with the range of resistance supplied in R. Thus, if the first test has shown the resistance of

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[1] Since the theorem of Art. 166 is only true when the current has attained a condition of steady flow. When S has considerable *self-induction*, as is the case when it consists of a coil, and still more if it has an iron core, a violent disturbance of the galvanometer may result if K_2 is depressed before K_1, although P/Q may equal R/S.

S to be between 213 and 214 ohms, the values $P=1000$ and $Q=100$ may be used, since, with these values, P being 10 times Q, a balance will be given when R is 10 times S, so that the balancing value of R will be between 2130 and 2140 ohms. The box now allows this range to be divided into 10 parts. The values $P=1000$ and $Q=10$ would not admit of a possible balance, since a value of R of above 21,300 ohms would be required. These values of P and Q would, however, be suitable if the preliminary test had shown the resistance of S to be between 21 and 22 ohms.

When the resistance of S is greater than the highest possible value of R, no balance will be possible when $P=Q$. In such cases Q must be made a multiple of, either 10 times or 100 times, P, and the value of S determined as the same multiple of the balancing resistance of R.

Measurement of the Variation of Resistance of a Metal with Rise of Temperature (B)

170. The coils of a resistance box are always wound with wire composed of platinoid, or some other alloy the resistance of which is scarcely affected by variations of temperature. Such a variation always exists with pure metals. To observe this, measure the resistance of a coil of iron wire immersed in distilled water, first with the water at the temperature of the air, and again when raised to the boiling-point. The wire must be connected to the box by long thick copper wires of very low resistance; the resistances of these connecting wires must be measured separately and allowed for, and they must make contact with the given wire below the surface of the water, or serious error may result from their junctions not being at the same temperature (thermo-electric effects). For the same reason the measuring apparatus must not be so near the heater as to be warmed by it.

Deduce from the results the coefficient of increase of resistance referred to the resistance of the metal at 0° C., assuming the resistance to vary proportionately with the temperature.

THE MEASUREMENT OF ELECTROMOTIVE FORCE AND POTENTIAL DIFFERENCE

Two rough methods have already been described as laboratory exercises (Arts. 155 and 157).

Direct Comparison of the Electromotive Forces of Cells by a Galvanometer (B)

171. The method depends upon the fact that, if the resistance of a wire connecting the terminals of a cell is very much greater than that of the cell, the current in the wire is practically proportional to the E.M.F. of the cell and independent of its resistance.

Connect the cells in succession through a high resistance with a sensitive galvanometer. If the highest resistance available is not sufficient to reduce the deflection to a convenient degree, the galvanometer must be shunted in addition. Record the deflections. If these do not exceed 20°, the currents, and consequently the E.M.F.'s, may be regarded as proportional to them, otherwise the calibration curve of the galvanometer must be known (Art. 163).

As an exercise on this method, compare the E.M.F.'s of a Daniell's and a Leclanché's cell, and, assuming the E.M.F. of the Daniell's cell to be 1·10 volts, find that of the other. Then combine the cells in series, first acting with and then acting against one another. Measure the E.M.F.'s of the combination in each case, and compare the results with those deduced from theory.

Measurement of the Back Electromotive Force of a Voltameter (B)

172. In every case in which energy other than heat appears as the result of a current traversing any apparatus, the apparatus necessarily exerts an E.M.F. acting in opposition to the current. Illustrations are supplied by the water voltameter and the electric motor.

To measure the back E.M.F. of a water voltameter, use the method of Art. 171, measuring first the E.M.F. of an accumulator, and then that of the accumulator connected in series with the water voltameter. The back E.M.F. of the voltameter is given by the difference. Notice that its value is greater than that of a Daniell's cell, and consider what would result if the voltameter were connected in series with a Daniell's cell. Test your conclusion by measuring the E.M.F. of the combination.

Repeat the experiments, substituting an electrolytic cell consisting of plates of copper immersed in a saturated solution of sulphate of copper for the water voltameter. Consider the meaning of the result obtained.

Comparison of Electromotive Forces by the Potentiometer (A)

173. The arrangement of this important experiment is represented in Fig. 13. A constant current C is maintained in a long graduated wire BD by connecting it to an "auxiliary" battery A, which usually consists of two accumulators in series. One end of a branch circuit which includes a given cell S, a sensitive galvanometer G, and a contact key K, is connected to B, the other end terminating in a sliding contact at F. It is important to bear in mind that similar terminals of A and S are to be connected to B.

If, now, the fall of potential from B to D is greater than the E.M.F. of S, a position of F may be found such that no current flows through the galvanometer on completing the branch circuit by the key. When this is the case

$$E = C \times \textit{resistance of } BF$$

where E is the E.M.F. of S, and C the current in BD. The proof of this relation is simple.

The experiment is now repeated with S replaced by another cell of E.M.F. E′. Denoting by F′ the position of the slider that now gives a balance,

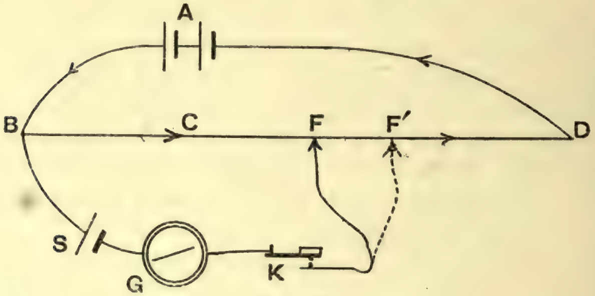

FIG. 13.

$$E' = C \times \textit{resistance of } BF',$$

so that the E.M.F.'s of S and S′ are proportional to the resistances of BF and BF′, or, assuming the wire to be uniform, simply to the lengths BF and BF′.

Arrange the connections as shown in Fig. 13. Before attempting to obtain a balance, it is advisable to test whether deflections in opposite directions are given with F well towards the left and well towards the right of BD. To obtain the actual E.M.F. of a cell it should be compared with another, the E.M.F. of which is known. A Daniell's cell does fairly well for such a standard, since its E.M.F.

never differs very much from 1·10 volts; but a still more accurate standard is supplied by the Weston cadmium cell, the E.M.F. of which, when prepared in a specified manner, is very accurately 1·0184 volts. When using a Weston cell, contact must only be made for a moment at K when an observation is required, as the cell, like Leclanché's cell, polarizes readily though temporarily, and the additional precaution should be taken of allowing the cell to rest for a minute before making the final observation. The same precaution is necessary with Leclanché's and every other polarizable cell.

As an exercise on the method, measure the E.M.F.'s of the different kinds of cells in use in the laboratory.

The number of cells required in the auxiliary battery is determined from the fact that the fall of potential from B to C, which is necessarily slightly less than the E.M.F. of the auxiliary battery, must be greater than the E.M.F. of any cell placed in the branch circuit.

Measurement of the Electromotive Forces of Cells by the Voltmeter (B)

174. The method supplies the simplest means of measuring E.M.F.'s. A voltmeter is essentially an ammeter (Art. 159*a*) of high resistance, its accuracy when used to measure E.M.F.'s depending on its high resistance (Art. 171). Its action being identical with that of an ammeter, the indication of a voltmeter depends directly upon the current traversing its coils; but since this is proportional to the potential difference between its terminals, the indications may be taken as a measure of this, and the instrument is graduated accordingly.

To measure the E.M.F.'s of cells, the terminals of the voltmeter are connected directly to those of the cells and the readings taken.

To test the Accuracy of the Readings of a Voltmeter (B)

175. Measure the E.M.F.'s of several accumulators separately by the method of Art. 173, then arrange different numbers of them in series, and measure the E.M.F.'s of the combinations. Compare the values indicated by the voltmeter with those deduced from theory, and construct a table of corrections. Also plot the corrections by a graph.

Measurement of the Potential Difference between two Points of an Electric Circuit by a Voltmeter (B)

176. The terminals of the voltmeter are simply connected to the two points by wires, the resistance of which must be inappreciable compared with that of the voltmeter, and the potential difference, as recorded by the voltmeter, taken.

The voltmeter acts as a shunt to the circuit, which is not broken by its addition.

This very important method assumes the resistance of the voltmeter to be so high that the current deflected through it does not appreciably disturb the electrical conditions already existing in the circuit. Judgment is sometimes necessary in deciding whether this may be assumed to be the case. Neglect of this precaution sometimes leads to the most remarkable results.

Notice as the essential distinction between a voltmeter and an ammeter, that whereas the resistance of a voltmeter, which is *added to* a circuit as a shunt, must be high, that of an ammeter, which is to be *included in* the circuit itself, should be low.

Measurement of the Resistance of a Cell (B)

177. Take the potential difference between the terminals of the cell by a voltmeter, or by the method of Art. 171 in which the galvanometer acts as a voltmeter, first with the terminals of the cell otherwise unconnected, and then with the terminals connected through wire of a known resistance. A fall of potential difference will follow the attachment of the wire. The resistance of the cell is the same fraction of the resistance of the circuit consisting of the cell and connecting wire that the drop in potential difference that follows the connection of the wire is of the total E.M.F. of the cell. The theory is quite simple.

Generally speaking, the resistance of the wire should not be less than an ohm, nor, except for possible precautions necessary in the use of accumulators, should it be much more.

ELECTRICAL ENERGY

Measurement of the Rate of Expenditure of Electrical Energy (B)

178. If V represents the potential difference in volts between two points on a circuit, and C the current in amperes in the circuit, the product VC represents the rate at which work is done in driving the current from one point to the other, or the rate at which electrical energy is expended, *i.e.* transformed into energy of other kinds, between the points (Art. 146). By simply taking the product, the rate of work is expressed in watts, but it may be expressed, if desired, in ergs per sec. by multiplying the product by 10^7.

In the case of a steady current the measurement of the rate of expenditure of electrical energy is a simple affair, it being only necessary to apply an ammeter to measure the current (Art. 159*a*), and a voltmeter to determine the potential difference between the points (Art. 176).

179. As an exercise on this relation, measure the rate of absorption of electrical energy in different glow-lamps, including lamps with metallic filaments. In these cases the energy is first transformed into heat, though a part is at once re-transformed into energy of radiation.

Determine, in addition, the candle-powers of the different lamps (Art. 106) and deduce values of their *efficiencies*, the *efficiency of a lamp* being defined as the ratio of its luminosity, expressed in candle-power, to the rate of absorption of electrical energy, expressed in watts.

Measurement of the Heat developed by a Current (B)

180. If the whole of the electrical energy expended between two points of a circuit is transformed into heat, the measure of the heat developed in t seconds by a current of C amperes traversing a conductor of resistance R ohms, is by Art. 178, since $V = CR$,

$$H = \frac{C^2 R t \times 10^7}{J} \text{ calories} \qquad \text{(i.)}$$

where J is the mechanical equivalent of heat. The value of J being $4{\cdot}2 \times 10^7$, in ergs per calorie, the above expression may be written

$$H = \frac{C^2 R t}{4{\cdot}2} \text{ calories} \qquad \text{(ii.)}$$

This expression is of such importance as to merit careful verification.

181. The wire in which the heat is developed should be of some alloy, such as manganin, the resistance of which varies but slightly with temperature. A length of 25 cms. of silk-covered manganin wire of No. 30 S.W.G. will have a resistance of about 1·2 ohms and will be convenient. The calorimeter may consist of a glass beaker of about 100 c.c. capacity. The ends of the manganin wire, which should be wound in a helix of four or five turns, may be soldered to the ends of two copper rods carried in an india-rubber cork which may be held by a clamp. The rods terminate at their upper ends in screws for connection. All kinds of framework for supporting the wire are objectionable, as it is very difficult to allow for the heat they absorb. The calorimeter is about four-fifths filled with distilled water, which is most conveniently measured by volume, and is placed in a jacket; the water should be initially a few degrees below the temperature of the air, and all precautions should be taken that have been described in dealing with the subject of calorimetry.

The current is conveniently supplied by a battery of two accumulators, and it is most accurately measured by passing it through a voltameter (Art. 159), though either a tangent galvanometer or an ammeter may be used. The circuit should include a rheostat, and this should be adjusted so that a convenient current is obtained, one of about two amperes with the coil suggested above. In using a voltameter it is essential that the current shall be nearly constant, and this may be tested by including a tangent galvanometer in the circuit in addition to the voltameter.

According to the arrangement suggested, we shall suppose the circuit to include the battery, a copper voltameter, a rheostat, and the calorimeter. It should also include a key for completing the circuit at a given instant.

Unlike the cases that have been dealt with in calorimetry, the rise of temperature will take place so slowly that, to obtain an accurate result, it will be necessary to allow a correction for the heat gained or lost by the calorimeter by convection and radiation. To make this correction, observe the temperature of the water in the calorimeter at the beginning and end of an interval of five minutes before connecting the battery, the water being gently stirred during the interval, and deduce the rate at which temperature is changing per minute. Now connect with the battery, and allow the current to flow for fifteen minutes, stirring gently during the time. Break contact at the end of the time, recording the temperature of the water after further stirring half a minute later. Stir for a further period of five minutes and again take the temperature. The mean rate of temperature variation before and after the experiment may be regarded as the rate at which the temperature of the water was varying during the experiment, independently of the variation caused by the current, and this must be allowed for in estimating the rise of temperature due to the current.

If the resistance of the wire is measured by any of the methods that have been described, preferably by that of Art. 168, if a standard coil of nearly equal resistance is available, the student will have sufficient data at his disposal to verify the relation given in Eq. ii. of Art. 180. The arrangement of the record and results is left to him, and with the experience he is now assumed to have gained, he should find little difficulty.

The Induction Coil

182. The coil is assumed to be of the ordinary form in use in the physical laboratory, the make and break being effected by a hammer contact-breaker actuated by the magnetisation of the central core.

See that the commutator is off, then connect the terminals of the primary coil to a set of six accumulators. A wise precaution consists in introducing a short length of lead wire fusing at not more than 10 amperes in the circuit, and many good coils would have been saved from ruin if this had always been done. Separate the terminals of the secondary coil by about half the length of the discharge that the coil is supposed to give. Release the spring by the screw at the base of column behind it, and adjust the screw at the head of the column so that contact is just completed at the contact breaker. Fix this screw by its clamping nut. Complete the circuit, and then gradually tighten the spring by the screw at the base until a rapid succession of flashes passes between the terminals of the secondary. If the lower screw is tightened too far, the attraction of the core upon the iron block of the contact breaker will be insufficient to break the contact, and a continuous current will traverse the coil that might produce serious damage but for the precaution suggested in the insertion of the fuse.

Avoid touching either discharging rod, or the result may be unpleasant.

If a longer discharge is required, separate the secondary terminals to a greater distance, and farther tighten the screw at the base, but it is not generally advisable to work a coil so as to give more than one-half its maximum length of discharge.

CHAPTER IX

SOUND

Measurement of the Frequency of Vibration of a Tuning-Fork (C)

183. The method assumed is that of a dropping plate. Smoke one surface of the plate by holding it in a flame, giving it a continuous horizontal movement during the process. A suitable flame is given by burning camphor; lamp flames are horrible. The deposit should not be too dense; when smoked, the plate should appear dusky, not opaque, by transmitted light. Fix the plate in the top of the frame by the catch, and attach a bristle to one prong of the fork by wax, or, better, by a screw fitted to the prong. Adjust the fork so that the bristle just touches the smoked surface. Sound the fork by drawing a peg just larger than the distance between the prongs sharply between them, and immediately release the plate. A waved trace will appear on the glass, each wave being formed by a complete vibration of the prong. Remove the glass from the frame.

For some distance from their origin, the waves will be so crowded together that it will be impossible to make accurate measurements upon them. Begin to count the waves from a point where they are quite distinct to as great a distance as the trace allows, counting from the centres, not from the crests, of the waves. Measure the distances, *a* and *b*, of the points at which the counting commenced and terminated respectively from the beginning of the trace. The times of fall through the distances a and b are $\sqrt{\frac{2a}{g}}$ and $\sqrt{\frac{2b}{g}}$ respectively, where $g=981$ (Art. 38), so that the time occupied in tracing the counted waves is

$$\frac{\sqrt{2}}{\sqrt{g}}(\sqrt{b}-\sqrt{a})$$

Deduce the frequency of the fork from these data.

Measurement of the Velocity of Sound in Air by the Method of Resonance (B)

184. If v denotes the velocity of a sound, or any other, wave, n the frequency of vibration, and λ the length of the wave,

$$v=n\times\lambda.$$

Be sure that you understand the reason of this.

Strike a tuning-fork of known frequency (Art. 183), and hold it with its prongs vibrating horizontally about an inch above the mouth of a tall jar, striking it again when its vibrations have ceased, and continuing to do so. Pour water into the jar until the contained air resonates most powerfully to the fork, and measure the length of the resonating column. Repeat this at least six times, and take the mean value of the length. But for the resistance offered by the external air to the reflected air waves as they ascend to the open end of the tube, this length would be exactly one-quarter the length of the waves. To correct for the action of the external air, add 0·8 of the radius of the tube to the resonating length. Then multiply this by 4 to obtain the wave length, and deduce the velocity of the waves.

The velocity of sound waves in all gases varies as the square root of the absolute temperature. Take the temperature of the air and apply this law to find the velocity of sound at 0° C. The actual velocity in dry air at 0° C. is 332·5 meters per second. It is slightly raised by the presence of water vapour, but is independent of pressure.

Verification of the Laws of Vibration of Strings

185. *The stretching force remaining constant, the frequency of vibration of a stretched string varies inversely as its length.* The apparatus required consists of a monochord and several tuning-forks of known frequencies.

Sound the fork of lowest pitch by striking it on a pad or the knee, and then applying the handle either to the table or the box of the monochord. Tighten the wire of the monochord so that the note it emits when plucked is slightly lower than that of the fork; then, using the bridge, shorten the wire until its note is in unison with that of the fork. This should be possible even with an unmusical ear; when the wire and fork sound together, beats are heard as unison is approached, the beats, at first rapid, becoming slower, and finally vanishing at unison. They may even be felt on touching the sounding box lightly with the fingers. A verification consists in placing a light paper rider on the wire, and applying the sounding fork to the bridge, the wire not being plucked in this case. As unison is approached, the rider becomes agitated, the wire taking up the motion of the fork by resonance, until when the correspondence between the frequencies of the wire and fork is very close, the rider is thrown off. Unison having been obtained, measure the length of the vibrating section of the wire.

Repeat the experiment with other forks, keeping the stretching force constant, and readjusting the bridge for each. Arrange the results in a table, the last column of which contains the products of the lengths of the vibrating sections and the corresponding frequencies. For the verification of the law, this product should be constant.

186. *The length of a stretched wire remaining constant, its frequency of vibration varies directly as the square root of the stretching force.* Use the wire that is stretched by the addition of a weight. It will at once be recognised by the ear that when the weight is quadrupled the pitch of the note is raised an octave. A more complete verification may be carried out as follows: tighten the second, fixed, wire so that it emits the same note as the first when this is stretched by the smallest weight, and shorten the fixed wire by the bridge to bring it into unison with the notes emitted by the first when the stretching force is increased by the addition of different weights. The arrangement of the data in the manner necessary to show the verification of the law is left to the student.

187. *Measurement of the Frequency of Vibration of a given Note by the Monochord* (C).—The note will be assumed to be that of a tuning-fork. Stretch the wire of the sonometer by a weight, and sound the fork. The most convenient weight is such as causes the full length of the wire to emit a note slightly below that of the fork. Shorten the wire by the bridge until its note is in unison with that of the fork. Then apply the equation for the frequency of vibration of the wire,

$$n = \frac{1}{2l}\sqrt{\frac{T}{\rho}}$$

where l is the length of the vibrating section in cms., T the stretching force in dynes, and ρ the mass of a cm. of the wire. The equation is derived from purely mechanical principles and is quite independent of any study of sound. To determine ρ, cut off a measured length of the wire and weigh it. If the weights are given in lbs., remember that 1 lb. = 453·6 grammes.

Instead of attempting to obtain perfect unison, a more exact method is to bring the note of the wire up towards that of the fork until the beats, which are getting slower, occur at the rate of about 4 per second. Measure the number of beats as accurately as possible. This number is that by which the frequency of the fork exceeds that of the wire.

188. *Harmonic Modes of Vibration.*—Use the full length of the wire. Pluck at about the centre. The note given is the *fundamental.* The stretching force should be adjusted so that this note is fairly low. Next, *damp* the centre of the wire by touching it fairly, but not too firmly, with the finger. Pluck the wire at about the middle of one of the two sections, immediately removing the damping finger. The wire now vibrates, in two segments, in its *first harmonic mode.* The note is the octave, its frequency being twice that of the fundamental.

Damp at a third of the length, plucking the centre of the smaller section, immediately removing the damping finger as before. The wire now vibrates in three segments in its *second harmonic mode*, with a frequency three times that of the fundamental. Proceed similarly to obtain farther harmonic modes.

CHAPTER X

HOW TO RECORD RESULTS

In order to illustrate how the results of physical experiments should be entered by the student, a few examples are here added.

Experiment 1. *Measurement of Specific Gravity of Methylated Spirit.*

The method adopted was that described in Art. 18 of the "Notes."

Mass of bottle	19 3526 grms.	
„ „ + water at 18°·1 C. .	68·3513 „	
hence mass of water .		48·9987 grms.
„ „ + spirit at 18°·2 C. .	59·4907 grms.	
hence mass of spirit .		40·1381 grms.

The volumes of water and spirit being the same, the sp. gr. of the spirit, referred to the water actually used, is

$$\frac{40\cdot1381}{48\cdot9987}=\cdot82105.$$

The sp. gr. of water at 18°·1 C. is ·998635 (Table I., p. 135), hence the sp. gr. of the spirit at 18°·2 C. is

$$\cdot82105\times\cdot998635=\cdot81805.$$

The experiment was repeated twice, the three values being

Sp. gr. at 18°·2 = ·81805 (above)
„ „ 18°·3 = ·81807
„ „ 18°·1 = ·81819

Mean value at **18°·2 C. = ·81810**

Another exp. gave for the sp. gr. at } 33°·5 C. ·80457
so that the sp. gr. decreases ·00090 for a degree.

The greatest difference from the mean in the three determinations corresponds to a change of 0·1 deg. in the temperature of the spirit. Hence the importance of observing the temperature.

The above is sufficient for most purposes. To obtain the highest accuracy, however, the weighings must be corrected for buoyancy of the surrounding air (Art. 14 and Table II.). The effect of this will be found to increase the values for the sp. gr. by ·00024, so that the corrected mean for the sp. gr. at 18°·2 C. is **·81834**.

EXPERIMENT 2. *Verification of Boyle's Law.*

The experiment was carried out as described in Art. 35.

Height of barometer = 75·85 cms.

Height of top of closed limb, corrected for end, assumed spherical = 16·65 − $\frac{1}{3}$ of ·45 = 16·50 cms.

	(i) Height in Open Limb (cms.).	(ii) Height in Closed Limb (cms.).	(iii) p=diff. bet. (ii) and (i)+ht. of Barometer.	(iv) v=diff. bet. ht. of top of Closed Limb and (i).	pv.
1	7·32	3·01	80·16	13·49	1081
2	14·50	4·00	86·35	12·50	1079
3	22·42	4·96	93·31	11·54	1077
4	35·93	6·33	105·45	10·17	1072
5	53·36	7·72	121·49	8·78	1067
6	64·76	8·47	132·14	8·03	1061
7	77·35	9·17	144·03	7·33	1056
8	88·54	9·69	154·70	6·81	1054

The continued decrease in the values of pv suggests that the cross section of the closed limb increases upwards. That this was the case, so far as the outside of the tube was concerned, was verified by a micrometer gauge.

Assuming the section to vary uniformly, it is possible to apply a correction for this, but the theory of the correction is beyond the scope of this work. The corrected values are: 1020, 1024, 1026, 1028, 1028, 1026, 1024, 1023. The mean of these is 1025, and the average divergence from the mean, 2, corresponds to an error of about 0·02 cms. in reading the height in the closed limb.

EXPERIMENT 3. *Specific Heat of Lead* (Art. 126).

Mass of lead	216·9 grms.
„ copper calorimeter . . .	111·3 „

The sp. ht. of copper being ·095, the calorimeter is thermally equivalent to 111·3 × ·095 = 10·6 grms. of water, a quantity known as the *thermal equivalent* of the calorimeter.

Water = 100 c.c. = 100 grms.

Hence the thermal equivalent of the calorimeter and water together is 110·6.

Temp. of water in boiler . . . 99°·9

The metal was heated for an hour.

Initial temp. of water in calorimeter . 16°·35

The metal was then introduced, 3 seconds being occupied in transferring the heating tube to the neighbourhood of the calorimeter, and 2 seconds more in transferring the metal from the tube to the calorimeter. The metal was kept in gentle movement in the water for 1·5 minutes, the thermometer then reintroduced, the movement of the metal continued, and the temperature taken half a minute later.

Final temp. of water in calorimeter . . .	21°·15
„ „ after 2 minutes more . .	21°·08
„ „ „ 2 „ . .	21°·00

Taking the final temperature as 21°·15, and equating the heat lost by the metal to that gained by the calorimeter and contained water,

$$216{\cdot}9 \times s \times (99{\cdot}9 - 21{\cdot}15) = 110{\cdot}6 \times (21{\cdot}15 - 16{\cdot}35),$$

from which $s = {\cdot}03110.$

The experiment as so far described is sufficient for elementary work, but it is very important that it should be repeated. From the data supplied, it is, however, a simple matter to apply a correction for the obvious fact that the calorimeter and water were cooling before it became possible to record their temperature at the end of the experiment. If the full loss of temperature by radiation is assumed to have acted from 15 seconds after the introduction of the metal, s is found to be ·03145.

The experiment was repeated twice, the three values of s being ·03145, ·03153, and ·03192, the mean being ·03163.

The thermometer used was graduated in tenths of a degree, estimation being made by eye to tenths of a scale division, *i.e.* hundredths of a degree. It is readily seen that an error of observation of a hundredth of a degree would affect the calculated value of s by ·00006, so that the fourth significant figure has little value.

To apply a correction for the heat lost by the metal during the 2 seconds occupied in its transference from the heating tube to the calorimeter, an experiment was carried out in which 10 seconds were allowed to elapse in the transference. The value of s obtained was ·03098. The additional 8 seconds consequently resulted in a decrease of ·00065 in the calculated value of s, 2 seconds would have resulted in a loss of ·000016, and the final corrected value of the sp. ht. of lead becomes

·03179,

which is rather higher than the generally accepted value.

Experiment 4. *Focal Length of a Convex Lens (marked "4")* (Art. 70).

A piece of wire gauze illuminated by sodium light was used as an object. A second gauze was used for a screen, and was so adjusted that when tested for parallax, it coincided in position with the image of the first.

Correction for "p."—The object and the lens, mounted in stands on the optical bench, were brought into simultaneous contact with the ends of a horizontal rod 19·18 cms. long. The thickness of the lens, tested by callipers, was ·34 cm. The actual distance between the object and the centre of the lens was therefore 19·35 cms. The scale reading of the stand carrying the object was 9·98, and that of the stand carrying the lens 29·30 cms., the difference being 19·32, so that a correction of + ·03 has to be added to the difference to give the actual distance from the object to the centre of the lens.

Correction for "q."—The lens and screen were similarly brought into contact with the ends of the rod. The scale readings were 34·24 and 53·40, the difference being 19·16. The actual distance between the centre of the lens and the screen being 19·35, a correction of + ·19 has to be added to the difference to give the value of q.

Measurements. I. Scale reading of object 8·00, and of lens 97·97. Difference = 89·97, and $p = 89{\cdot}97 + {\cdot}03 = 90$ cms.

Five adjustments of the screen were made by the method of parallax, the scale readings being 135·85 : 135·85 : 135·85 : 135·85 : and 135·65. The mean is 135·81, the value of q, $37{\cdot}84 + {\cdot}19 = 38{\cdot}03$ cms. The value of f calculated from these values from the formula of Art. 63 is **26·73** cms.

II. Scale reading of object 8·00, of lens 87·97. Diff. = 79·97, hence $p = 79{\cdot}97 + {\cdot}03 = 80$ cms.

Scale readings of screen—128·10 : 128·20 : 128·20 : 128·10 : 128·15. The mean is 128·15, the deduced value of q, 40·37, and the resulting value of f, **26·83** cms.

III. Scale reading of object 8·00, of lens 77·97. Diff. = 69·97, hence $p = 69{\cdot}97 + {\cdot}03 = 70$ cms.

Scale readings of screen—121·00 : 121·00 : 121·20 : 121·10 : 121·25. Mean = 121·11. Hence $q = 43{\cdot}33$, and $f =$ **26·76** cms.

Summary. The three values obtained for f being

26·73 26·83 26·76 cms.

the mean is

26·77 cms.

which may be regarded as the focal length of the lens for sodium light.

EXPERIMENT 5. *Resistance of a Daniell's Cell.*

The experiment was carried out as described in Art. 153, except that six values of box resistance were taken, these being combined in three pairs for the purposes of the calculation.

The galvanometer was shunted by about 30 cms. of German silver wire of No. 26 S.W.G. so as to reduce the deflection with no resistance in the box to a convenient degree.

No.	R. (Box.)	Deflections.					tan D.	(R+X)tan D.
		N.W.	S.E.	N.E.	S.W.	Mean. (D.)		
1	0	65·1	65·4	67·7	67·1	66·3	2·2781	2·28
2	1	45·9	46·6	47·7	47·0	46·8	1·0649	2·13
3	2	34·7	35·2	35·6	35·1	35·2	·7054	2·12
4	3	27·5	28·1	28·2	27·8	27·9	·5295	2·12
5	4	22·8	23·4	23·4	22·9	23·1	·4276	2·14
6	5	19·2	20·0	19·9	19·2	19·6	·3551	2·13

On obtaining the mean deflections, the measurements were divided in pairs and the value of X (Art. 153) found from each pair by the formula given in the Art. The following values of X were obtained :—

From 1 and 4	0·91
„ 2 and 5	1·02
„ 3 and 6	1·04
Mean	0·99

The whole series of measurements was repeated with closely corresponding results, the three values obtained for X being

0·92, 1·01, and 1·02 ohms.

The resistance of the circuit exclusive of the box and cell was measured by the method of Art. 169 and found to be 0·34 ohms. Consequently the resistance of the cell was

0·65 ohms.

The values of (R + X)tan D in the last column were obtained by taking the mean value of X as 1. The numbers in this column should be constant, but for the apparent increase in the resistance of the cell with smaller currents.

The low values for X with greater currents are probably due to the liquid in the pores of the porous pot being heated, since the resistance of an electrolyte, unlike that of a metal, decreases with rising temperature.

APPENDIX

TABLE I

Specific Gravity of Water at Different Temperatures (Rosetti)

The specific gravity of water at 4° C. is defined as 1.

° C.	*Sp. gr.*	° C.	*Sp. gr.*
0	·999871	19	·998460
1	·999928	20	·998259
2	·999969	21	·998047
3	·999991	22	·997826
4	1·000000	23	·997600
5	·999990	24	·997367
6	·999970	25	·997120
7	·999933	26	·996866
8	·999886	27	·996603
9	·999824	28	·996330
10	·999747	29	·996050
11	·999655	30	·995765
12	·999549	40	·99235
13	·999430	50	·98821
14	·999299	60	·98339
15	·999160	70	·97794
16	·999002	80	·97193
17	·998841	90	·96556
18	·998654	100	·95864

TABLE II

Correction in Weighing due to Buoyancy of Air

The quantity to be added to the apparent mass as given in the operation of weighing is

$$ma\frac{\frac{1}{s}-\frac{1}{d}}{1-\frac{a}{s}}$$

where m = mass of the "weights."
d = sp. gr. of the "weights."
a = sp. gr. of surrounding air.
s = mean sp. gr. of the weighed body.

The following table of corrections, which shows the importance of the correction when the sp. gr. of the weighed body is low, is calculated from the formula, upon the assumptions that the weights are of brass of sp. gr. 8·4, that the air is at 17° C., half saturated with water vapour, and under a pressure of 76 cms. of mercury. Under these conditions $a =$ ·00122.

If the temperature is between 13° C. and 22° C., if the air is either dry or fully saturated with water vapour, if the pressure is between 72 and 80 cms., and if the sp. gr. of the weighed body exceeds ·8, the error involved in applying the corrections given would in no case exceed ·01, so that the corrected mass would be given to within 1 part in 10,000, which is sufficiently accurate for nearly every purpose.

Mean Sp. Gr. of Body Weighed (*s*).	Mass to be added for every Hundred Grammes (*c*).	*s*.	*c*.	*s*.	*c*.
0·1	1·2175	1·2	·0872	5·0	·0099
0·2	·5992	1·3	·0794	6·0	·0058
0·3	·3931	1·4	·0726	7·0	·0029
0·4	·2913	1·5	·0679	8·0	·0008
0·5	·2301	1·6	·0617	9·0	– ·0009
0·6	·1889	1·7	·0572	10·0	– ·0023
0·7	·1598	1·8	·0532	11·0	– ·0034
0·8	·1380	1·9	·0497	12·0	– ·0043
0·9	·1210	2·0	·0465	13·0	– ·0051
1·0	·1075	3·0	·0261	14·0	– ·0058
1·1	·0964	4·0	·0160		

TABLE III

Pressure of Saturated Water Vapour

° C.	*Pressure in Cms. of Mercury.*	° C.	*Pressure in Cms. of Mercury.*
0	0·46	17	1·44
2	0·53	18	1·54
4	0·61	19	1·63
6	0·70	20	1·74
8	0·80	21	1·85
10	0·91	22	1·97
12	1·04	23	2·09
14	1·19	24	2·22
15	1·27	25	2·36
16	1·35		

TABLE IV

Wave Lengths of some Lines in the Spectrum

The wave lengths are given in tenth-meters, a tenth-meter being 10^{-10} meter, or 10^{-8} centimeter.

Substance.	*Wave Length.*
Potassium α	7685
Lithium α	6705
Hydrogen α	6562
Lithium β	6102
Sodium (D_1)	5895
,, (D_2)	5889
Hydrogen β	4861
Hydrogen γ	4340
Hydrogen δ	4101
Potassium β	4080

	0	1	2	3	4	5	6	7	8	9	1	2	3	4	5	6	7	8	9
10	0000	0043	0086	0128	0170						4	9	13	17	21	26	30	34	38
						0212	0253	0294	0334	0374	4	8	12	16	20	24	28	32	37
11	0414	0453	0492	0531	0569						4	8	12	15	19	23	27	31	35
						0607	0645	0682	0719	0755	4	7	11	15	19	22	26	30	33
12	0792	0828	0864	0899	0934	0969					3	7	11	14	18	21	25	28	32
							1004	1038	1072	1106	3	7	10	14	17	20	24	27	31
13	1139	1173	1206	1239	1271						3	7	10	13	16	20	23	26	30
						1303	1335	1367	1399	1430	3	7	10	12	16	19	22	25	29
14	1461	1492	1523	1553							3	6	9	12	15	18	21	24	28
					1584	1614	1644	1673	1703	1732	3	6	9	12	15	17	20	23	26
15	1761	1790	1818	1847	1875	1903					3	6	9	11	14	17	20	23	26
							1931	1959	1987	2014	3	5	8	11	14	16	19	22	25
16	2041	2068	2095	2122	2148						3	5	8	11	14	16	19	22	24
						2175	2201	2227	2253	2279	3	5	8	10	13	15	18	21	23
17	2304	2330	2355	2380	2405	2430					3	5	8	10	13	15	18	20	23
							2455	2480	2504	2529	2	5	7	10	12	15	17	19	22
18	2553	2577	2601	2625	2648						2	5	7	9	12	14	16	19	21
						2672	2695	2718	2742	2765	2	5	7	9	11	14	16	18	21
19	2788	2810	2833	2856	2878						2	4	7	9	11	13	16	18	20
						2900	2923	2945	2967	2989	2	4	6	8	11	13	15	17	19
20	3010	3032	3054	3075	3096	3118	3139	3160	3181	3201	2	4	6	8	11	13	15	17	19
21	3222	3243	3263	3284	3304	3324	3345	3365	3385	3404	2	4	6	8	10	12	14	16	18
22	3424	3444	3464	3483	3502	3522	3541	3560	3579	3598	2	4	6	8	10	12	14	15	17
23	3617	3636	3655	3674	3692	3711	3729	3747	3766	3784	2	4	6	7	9	11	13	15	17
24	3802	3820	3838	3856	3874	3892	3909	3927	3945	3962	2	4	5	7	9	11	12	14	16
25	3979	3997	4014	4031	4048	4065	4082	4099	4116	4133	2	3	5	7	9	10	12	14	15
26	4150	4166	4183	4200	4216	4232	4249	4265	4281	4298	2	3	5	7	8	10	11	13	15
27	4314	4330	4346	4362	4378	4393	4409	4425	4440	4456	2	3	5	6	8	9	11	13	14
28	4472	4487	4502	4518	4533	4548	4564	4579	4594	4609	2	3	5	6	8	9	11	12	14
29	4624	4639	4654	4669	4683	4698	4713	4728	4742	4757	1	3	4	6	7	9	10	12	13
30	4771	4786	4800	4814	4829	4843	4857	4871	4886	4900	1	3	4	6	7	9	10	11	13
31	4914	4928	4942	4955	4969	4983	4997	5011	5024	5038	1	3	4	6	7	8	10	11	12
32	5051	5065	5079	5092	5105	5119	5132	5145	5159	5172	1	3	4	5	7	8	9	11	12
33	5185	5198	5211	5224	5237	5250	5263	5276	5289	5302	1	3	4	5	6	8	9	10	12
34	5315	5328	5340	5353	5366	5378	5391	5403	5416	5428	1	3	4	5	6	8	9	10	11
35	5441	5453	5465	5478	5490	5502	5514	5527	5539	5551	1	2	4	5	6	7	9	10	11
36	5563	5575	5587	5599	5611	5623	5635	5647	5658	5670	1	2	4	5	6	7	8	10	11
37	5682	5694	5705	5717	5729	5740	5752	5763	5775	5786	1	2	3	5	6	7	8	9	10
38	5798	5809	5821	5832	5843	5855	5866	5877	5888	5899	1	2	3	5	6	7	8	9	10
39	5911	5922	5933	5944	5955	5966	5977	5988	5999	6010	1	2	3	4	5	7	8	9	10
40	6021	6031	6042	6053	6064	6075	6085	6096	6107	6117	1	2	3	4	5	6	8	9	10
41	6128	6138	6149	6160	6170	6180	6191	6201	6212	6222	1	2	3	4	5	6	7	8	9
42	6232	6243	6253	6263	6274	6284	6294	6304	6314	6325	1	2	3	4	5	6	7	8	9
43	6335	6345	6355	6365	6375	6385	6395	6405	6415	6425	1	2	3	4	5	6	7	8	9
44	6435	6444	6454	6464	6474	6484	6493	6503	6513	6522	1	2	3	4	5	6	7	8	9
45	6532	6542	6551	6561	6571	6580	6590	6599	6609	6618	1	2	3	4	5	6	7	8	9
46	6628	6637	6646	6656	6665	6675	6684	6693	6702	6712	1	2	3	4	5	6	7	7	8
47	6721	6730	6739	6749	6758	6767	6776	6785	6794	6803	1	2	3	4	5	5	6	7	8
48	6812	6821	6830	6839	6848	6857	6866	6875	6884	6893	1	2	3	4	4	5	6	7	8
49	6902	6911	6920	6928	6937	6946	6955	6964	6972	6981	1	2	3	4	4	5	6	7	8
50	6990	6998	7007	7016	7024	7033	7042	7050	7059	7067	1	2	3	3	4	5	6	7	8

	0	1	2	3	4	5	6	7	8	9	1	2	3	4	5	6	7	8	9
51	7076	7084	7093	7101	7110	7118	7126	7135	7143	7152	1	2	3	3	4	5	6	7	8
52	7160	7168	7177	7185	7193	7202	7210	7218	7226	7235	1	2	2	3	4	5	6	7	7
53	7243	7251	7259	7267	7275	7284	7292	7300	7308	7316	1	2	2	3	4	5	6	6	7
54	7324	7332	7340	7348	7356	7364	7372	7380	7388	7396	1	2	2	3	4	5	6	6	7
55	7404	7412	7419	7427	7435	7443	7451	7459	7466	7474	1	2	2	3	4	5	5	6	7
56	7482	7490	7497	7505	7513	7520	7528	7536	7543	7551	1	2	2	3	4	5	5	6	7
57	7559	7566	7574	7582	7589	7597	7604	7612	7619	7627	1	2	2	3	4	5	5	6	7
58	7634	7642	7649	7657	7664	7672	7679	7686	7694	7701	1	1	2	3	4	4	5	6	7
59	7709	7716	7723	7731	7738	7745	7752	7760	7767	7774	1	1	2	3	4	4	5	6	7
60	7782	7789	7796	7803	7810	7818	7825	7832	7839	7846	1	1	2	3	4	4	5	6	6
61	7853	7860	7868	7875	7882	7889	7896	7903	7910	7917	1	1	2	3	4	4	5	6	6
62	7924	7931	7938	7945	7952	7959	7966	7973	7980	7987	1	1	2	3	3	4	5	6	6
63	7993	8000	8007	8014	8021	8028	8035	8041	8048	8055	1	1	2	3	3	4	5	5	6
64	8062	8069	8075	8082	8089	8096	8102	8109	8116	8122	1	1	2	3	3	4	5	5	6
65	8129	8136	8142	8149	8156	8162	8169	8176	8182	8189	1	1	2	3	3	4	5	5	6
66	8195	8202	8209	8215	8222	8228	8235	8241	8248	8254	1	1	2	3	3	4	5	5	6
67	8261	8267	8274	8280	8287	8293	8299	8306	8312	8319	1	1	2	3	3	4	5	5	6
68	8325	8331	8338	8344	8351	8357	8363	8370	8376	8382	1	1	2	3	3	4	4	5	6
69	8388	8395	8401	8407	8414	8420	8426	8432	8439	8445	1	1	2	2	3	4	4	5	6
70	8451	8457	8463	8470	8476	8482	8488	8494	8500	8506	1	1	2	2	3	4	4	5	6
71	8513	8519	8525	8531	8537	8543	8549	8555	8561	8567	1	1	2	2	3	4	4	5	5
72	8573	8579	8585	8591	8597	8603	8609	8615	8621	8627	1	1	2	2	3	4	4	5	5
73	8633	8639	8645	8651	8657	8663	8669	8675	8681	8686	1	1	2	2	3	4	4	5	5
74	8692	8698	8704	8710	8716	8722	8727	8733	8739	8745	1	1	2	2	3	4	4	5	5
75	8751	8756	8762	8768	8774	8779	8785	8791	8797	8802	1	1	2	2	3	3	4	5	5
76	8808	8814	8820	8825	8831	8837	8842	8848	8854	8859	1	1	2	2	3	3	4	5	5
77	8865	8871	8876	8882	8887	8893	8899	8904	8910	8915	1	1	2	2	3	3	4	4	5
78	8921	8927	8932	8938	8943	8949	8954	8960	8965	8971	1	1	2	2	3	3	4	4	5
79	8976	8982	8987	8993	8998	9004	9009	9015	9020	9025	1	1	2	2	3	3	4	4	5
80	9031	9036	9042	9047	9053	9058	9063	9069	9074	9079	1	1	2	2	3	3	4	4	5
81	9085	9090	9096	9101	9106	9112	9117	9122	9128	9133	1	1	2	2	3	3	4	4	5
82	9138	9143	9149	9154	9159	9165	9170	9175	9180	9186	1	1	2	2	3	3	4	4	5
83	9191	9196	9201	9206	9212	9217	9222	9227	9232	9238	1	1	2	2	3	3	4	4	5
84	9243	9248	9253	9258	9263	9269	9274	9279	9284	9289	1	1	2	2	3	3	4	4	5
85	9294	9299	9304	9309	9315	9320	9325	9330	9335	9340	1	1	2	2	3	3	4	4	5
86	9345	9350	9355	9360	9365	9370	9375	9380	9385	9390	1	1	2	2	3	3	4	4	5
87	9395	9400	9405	9410	9415	9420	9425	9430	9435	9440	0	1	1	2	2	3	3	4	4
88	9445	9450	9455	9460	9465	9469	9474	9479	9484	9489	0	1	1	2	2	3	3	4	4
89	9494	9499	9504	9509	9513	9518	9523	9528	9533	9538	0	1	1	2	2	3	3	4	4
90	9542	9547	9552	9557	9562	9566	9571	9576	9581	9586	0	1	1	2	2	3	3	4	4
91	9590	9595	9600	9605	9609	9614	9619	9624	9628	9633	0	1	1	2	2	3	3	4	4
92	9638	9643	9647	9652	9657	9661	9666	9671	9675	9680	0	1	1	2	2	3	3	4	4
93	9685	9689	9694	9699	9703	9708	9713	9717	9722	9727	0	1	1	2	2	3	3	4	4
94	9731	9736	9741	9745	9750	9754	9759	9763	9768	9773	0	1	1	2	2	3	3	4	4
95	9777	9782	9786	9791	9795	9800	9805	9809	9814	9818	0	1	1	2	2	3	3	4	4
96	9823	9827	9832	9836	9841	9845	9850	9854	9859	9863	0	1	1	2	2	3	3	4	4
97	9868	9872	9877	9881	9886	9890	9894	9899	9903	9908	0	1	1	2	2	3	3	4	4
98	9912	9917	9921	9926	9930	9934	9939	9943	9948	9952	0	1	1	2	2	3	3	4	4
99	9956	9961	9965	9969	9974	9978	9983	9987	9991	9996	0	1	1	2	2	3	3	3	4

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Angle.									
Degrees.	Radians.	Chord.	Sine.	Tangent.	Co-tangent.	Cosine.			
0°	0	0	0	0	∞	1	1·414	1·5708	90°
1	·0175	·017	·0175	·0175	57·2900	·9998	1·402	1·5533	89
2	·0349	·035	·0349	·0349	28·6363	·9994	1·389	1·5359	88
3	·0524	·052	·0523	·0524	19·0811	·9986	1·377	1·5184	87
4	·0698	·070	·0698	·0699	14·3007	·9976	1·364	1·5010	86
5	·0873	·087	·0872	·0875	11·4301	·9962	1·351	1·4835	85
6	·1047	·105	·1045	·1051	9·5144	·9945	1·338	1·4661	84
7	·1222	·122	·1219	·1228	8·1443	·9925	1·325	1·4486	83
8	·1396	·140	·1392	·1405	7·1154	·9903	1·312	1·4312	82
9	·1571	·157	·1564	·1584	6·3138	·9877	1·299	1·4137	81
10	·1745	·174	·1736	·1763	5·6713	·9848	1·286	1·3963	80
11	·1920	·192	·1908	·1944	5·1446	·9816	1·272	1·3788	79
12	·2094	·209	·2079	·2126	4·7046	·9781	1·259	1·3614	78
13	·2269	·226	·2250	·2309	4·3315	·9744	1·245	1·3439	77
14	·2443	·244	·2419	·2493	4·0108	·9703	1·231	1·3265	76
15	·2618	·261	·2588	·2679	3·7321	·9659	1·218	1·3090	75
16	·2793	·278	·2756	·2867	3·4874	·9613	1·204	1·2915	74
17	·2967	·296	·2924	·3057	3·2709	·9563	1·190	1·2741	73
18	·3142	·313	·3090	·3249	3·0777	·9511	1·176	1·2566	72
19	·3316	·330	·3256	·3443	2·9042	·9455	1·161	1·2392	71
20	·3491	·347	·3420	·3640	2·7475	·9397	1·147	1·2217	70
21	·3665	·364	·3584	·3839	2·6051	·9336	1·133	1·2043	69
22	·3840	·382	·3746	·4040	2·4751	·9272	1·118	1·1868	68
23	·4014	·399	·3907	·4245	2·3559	·9205	1·104	1·1694	67
24	·4189	·416	·4067	·4452	2·2460	·9135	1·089	1·1519	66
25	·4363	·433	·4226	·4663	2·1445	·9063	1·075	1·1345	65
26	·4538	·450	·4384	·4877	2·0503	·8988	1·060	1·1170	64
27	·4712	·467	·4540	·5095	1·9626	·8910	1·045	1·0996	63
28	·4887	·484	·4695	·5317	1·8807	·8829	1·030	1·0821	62
29	·5061	·501	·4848	·5543	1·8040	·8746	1·015	1·0647	61
30	·5236	·518	·5000	·5774	1·7321	·8660	1·000	1·0472	60
31	·5411	·534	·5150	·6009	1·6643	·8572	·985	1·0297	59
32	·5585	·551	·5299	·6249	1·6003	·8480	·970	1·0123	58
33	·5760	·568	·5446	·6494	1·5399	·8387	·954	·9948	57
34	·5934	·585	·5592	·6745	1·4826	·8290	·939	·9774	56
35	·6109	·601	·5736	·7002	1·4281	·8192	·923	·9599	55
36	·6283	·618	·5878	·7265	1·3764	·8090	·908	·9425	54
37	·6458	·635	·6018	·7536	1·3270	·7986	·892	·9250	53
38	·6632	·651	·6157	·7813	1·2799	·7880	·877	·9076	52
39	·6807	·668	·6293	·8098	1·2349	·7771	·861	·8901	51
40	·6981	·684	·6428	·8391	1·1918	·7660	·845	·8727	50
41	·7156	·700	·6561	·8693	1·1504	·7547	·829	·8552	49
42	·7330	·717	·6691	·9004	1·1106	·7431	·813	·8378	48
43	·7505	·733	·6820	·9325	1·0724	·7314	·797	·8203	47
44	·7679	·749	·6947	·9657	1·0355	·7193	·781	·8029	46
45°	·7854	·765	·7071	1·0000	1·0000	·7071	·765	·7854	45°
			Cosine.	Co-tangent.	Tangent.	Sine.	Chord.	Radians.	Degrees.
								Angle.	

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  [illegible]
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W[illegible]
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  [illegible]
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